IGNEOUS ROCKS AND THE DEPTHS OF THE EARTH

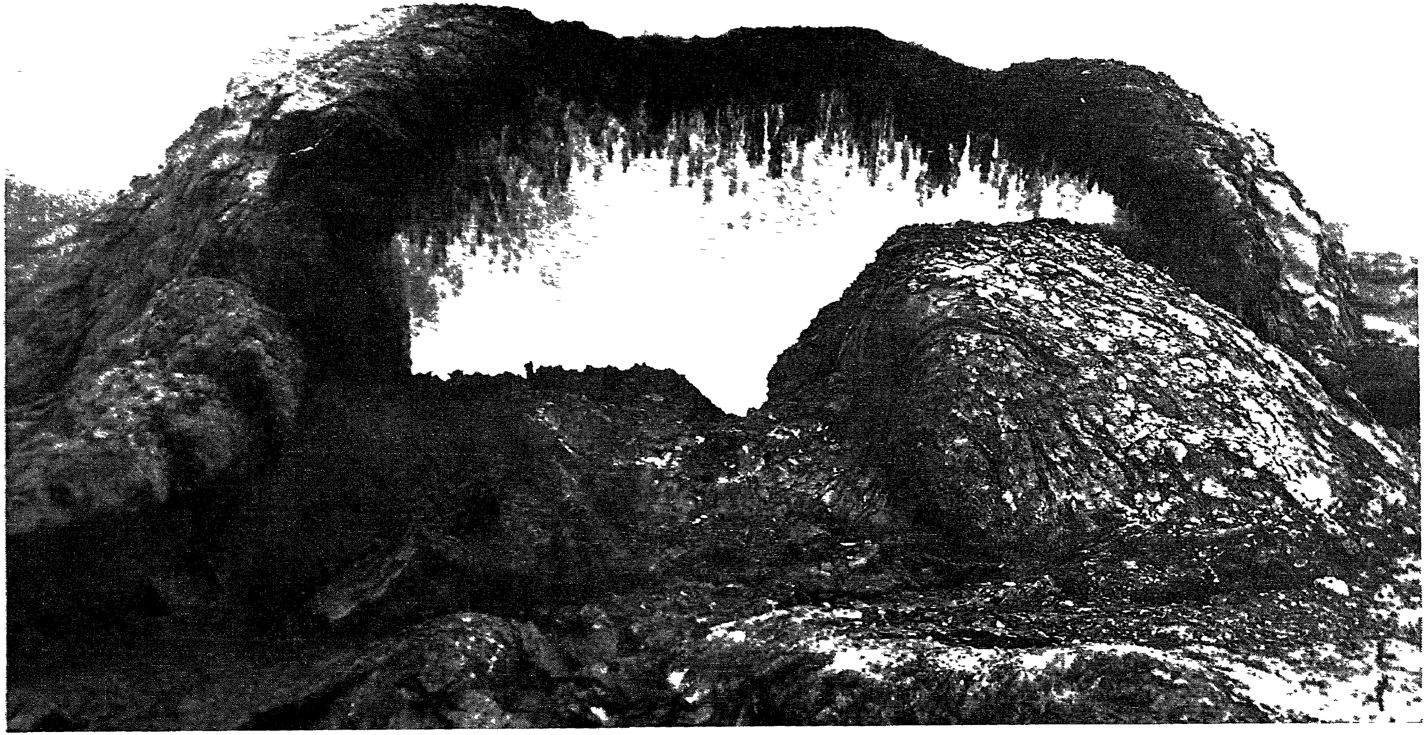

PLATE I (*Frontispiece*).—Glowing mouth of a cone built above a rift in the floor of Kilauea. The internal glow was bright yellow below, passing upward to orange and then red at the orifice. The structures shown are dripping stalactites of incandescent rock, fluxed by the emanating hot gas and by radiation from lava beneath. (*Photograph by T. A. Jaggar, Bull. Hawaiian Volcano Observatory, vol.* 9, 1921, *pp.* 73, 91.)

IGNEOUS ROCKS
AND THE
DEPTHS OF THE EARTH

Containing Some Revised Chapters of "Igneous Rocks and Their Origin" (1914)

BY

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"This earth of majesty"
SHAKESPEARE

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To my Wife
Inspiring Fellow Worker
This Book Is Dedicated

PREFACE

The lava lake of a Hawaiian or Samoan volcano with its fountains and tumultuous waves of liquid rock is "unearthly." The marveling observer thinks of sun and star, and soon comes to realize with peculiar liveliness that our camouflaged planet also is one of the heavenly bodies. All the material of visible rocks was once molten, "igneous"; there is increasing evidence that the great invisible interior of the globe was, and for the most part still is, too hot to crystallize. The earth is itself essentially a composite igneous rock, and a serious attempt to account for the rocks once molten leads automatically to a general "theory of the earth."

Because so little is known about the planet's origin and about the nature of its interior, some authorities believe the genesis of granite, andesite, syenite, basalt, and other standard species of rocks should be considered without systematic reference to the mysterious depths. However, none of these petrologists has obeyed his own prescription, but more or less unconsciously each has based his thought upon assumptions concerning the subcrustal materials, their distribution, and their activities. Meager as may be the definite facts proved by the cosmogonist and geophysicist, and uncertain as may be the general conclusions reached, these facts and conclusions are vital in the ultimate problem of visible rock. Any good explanation of the igneous rocks is sure to be modified as the cognate sciences continue to add new data, and yet its author is forbidden "the unctuous feeling" of dealing "only in solid facts." Necessarily speculative himself, he welcomes the reasoned speculations of others, rejecting only when observed facts compel the step.

Thus at present no comprehensive work on petrogenesis can be other than a report of progress of its author's own synthetic thought on the broad subject. The physicist has "created" and re-"created" the invisible atom, with practical results of the utmost significance for his science. In the words of R. B. Lindsay, the physicist "is coming more and more to realize that the data of atomic physics are so extremely complicated that without philosophical interpretation, *i.e.*, the introduction of new and satisfactory hypotheses, they are meaningless." Similarly the petrologist is of right pragmatic, and prepared to re-"create" the earth, which is so largely invisible and unattainable.

Quite apart from errors of detail contained in "Igneous Rocks and Their Origin" (1914), the theory of the earth there stated, while in principle retained, needs changes in some important respects. Since 1914, increase of valuable data from cosmogony, geophysics, experimental petrology, volcanology, and general geology has prompted a revision of the subject. The result is the present book, essentially a new book. A comparatively small part of the older text has been retained intact. Complete rewriting of chapters is the rule, new chapters and sixty new illustrations have been added, and seventy-five of the 1914 illustrations omitted. In order to indicate the difference of the two presentations and to tell at the very beginning the direction in which the main thought of this new work is directed, it has been given another title.

The more vital changes in opinion, argument, and speculative theory include the following: new doubt concerning the relation of the earth's contraction to mountain-building and to the ascent of igneous melts from depth; new emphasis on at least moderate horizontal displacement of large parts of the continental crust over the earth's body; new emphasis on magmatic stoping and the correlated abyssal pure melting of rocks—both on a scale considerably bigger than that imagined in 1914; less emphasis upon liquid immiscibility in magmas; more attention to the contrast in the magmatic conditions of early Pre-Cambrian time as against Paleozoic and later time, illustrating once again the mistake of accepting uniformitarianism as an infallible guide in geology; new stressing of the fact that no one process can explain the diversity of the igneous rocks, especially the multitude of "alkaline" types.

Certain omissions make further contrast with "Igneous Rocks and Their Origin." These comprise the whole of Chapter XXI, dealing with the petrology of the North American Cordillera; much of Chapter XIV, which summarized the general theory formulated in 1914; and the four long Appendixes.

The material of Chapters V and IX to XXIII, inclusive, is largely new, though based upon the fundamental assumption of the older book: that the crust of the earth is real, relatively thin, and resting upon a vitreous, highly rigid, but extremely weak, basaltic shell, continuous around the globe. However bold that postulate may be, it can hardly be more rash and "dangerous" than to assume general crystallinity for all the earth shells engaged in igneous action. While some writers believe the continental rocks (the Sial) to rest directly upon a thick, world-circling shell of crystalline peridotite, no one has yet seriously undertaken to show how that hypothesis can be made to match the facts of geology. The author sees no way of establishing

the correspondence. Some other published conceptions of the earth's depths are vague and do not permit even the beginning of a satisfactory scheme of petrogenesis. Under the circumstances the author feels somewhat as Vogt did when he made confession of a "modest scientific belief in authority." Petrology, as distinct from petrography, is still in the pioneer stage of development, and this book has been written not so much to advocate its own speculative scheme as to insist that petrology will make best progress by systematically examining all of the possible hypotheses relating to the earth's interior. If any of these is worth consideration at all, it is worth a book for its unfolding. What petrology now needs is a series of such elaborations, even of those ideas that some authorities may regard as "wild." The broadcasting of the results throughout the profession would tend to offset the subjectivity marring the discussion of any one fundamental hypothesis, and to stimulate investigation at critical points in the problem of petrogenesis.

In general, the technical terms used are more or less formally defined in the text, the corresponding references to be found in the Index. Here special note is made of four convenient adjectives, increasingly employed by petrologists. "Felsic" and "mafic" describe rocks actually crystallized. Felsic rocks are those largely composed of combinations of light-colored minerals, feldspars, feldspathoids, quartz; mafic rocks are those largely composed of combinations of dark-colored minerals, pyroxenes, olivines, amphiboles, micas, ores, etc. Both words are also used to describe relative proportions of light and dark minerals in the rocks of an igneous series. "Salic" will refer to both melts and rigid glasses, whose chemical analyses would yield by calculation relatively high proportions of light-colored "normative" or "standard" minerals; "femic" is the corresponding word to describe melts and rigid glasses that yield after similar treatment relatively high proportions of dark-colored, basic, normative minerals.

"Gabbroic" is used as the adjectival form of "gabbro" and is thus analogous with "granitic," the adjective corresponding to "granite." "Gabbroid" here means "more or less closely similar to, but not identical with, gabbro" or else "of the general habit of gabbro"; here the analogy is with "granitoid."

Full acknowledgment of help in assembling the many facts on which the revised general theory is based is out of the question. A partial measure of this debt is given by what would be a complete list of the general treatises on petrology and geology and by the bibliographical references through the book. Besides the notations of the 1914 volume there must be mentioned additional, valued aid from Dr.

L. H. Adams, Dr. N. L. Bowen, Prof. P. W. Bridgman, Dr. A. L. du Toit, Dr. C. N. Fenner, Prof. B. Gutenberg, Dr. A. L. Hall, Prof. A. Holmes, Dr. T. A. Jaggar, Dr. H. Jeffreys, Dr. L. V. Krige, Mr. W. D. Lambert, Prof. A. C. Lane, Prof. E. S. Larsen, Mr. E. G. Radley, Prof. J. E. Wolff, Dr. F. E. Wright, and Dr. W. A. Zisman, as well as the authorities in charge of the Sturgis Hooper (Harvard University), Shaler Memorial (Harvard University), and Carnegie Institution of Washington funds for the support of field studies. To Dr. H. S. Washington for a detailed, instructive critique of "Igneous Rocks and Their Origin" special thanks are due. Neither he nor any other of the author's friends should, of course, be held responsible for errors, new or old, in the present volume. Finally it is a pleasure to acknowledge the courtesy of Sir John Flett and of the Controller of the Government Stationery Office, London, for permission to copy the maps and sections represented in Figs. 21, 23 to 28 inclusive, 35, 111, and 117.

REGINALD ALDWORTH DALY.

CAMBRIDGE, MASS.,
April, 1933.

CONTENTS

IGNEOUS ROCKS
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CHAPTER I

ABSTRACT

A final philosophy of earth history must be largely founded upon the unshakable facts known about igneous rocks. If, therefore, any book on petrology is to help in the attainment of that distant goal, it distinguishes as clearly as possible between fact and theoretical deduction. The effort to make the following discussion of most use to others has led to its division into three parts. The first (Chapters II to VIII, inclusive) considers broadly the facts needing explanation. The second part (Chapters IX to XV, inclusive) contains the statement of a general eclectic theory. The remaining eight chapters sketch the result of applying the general theory to the separate major groups or "clans" of eruptive rocks. In order to keep the book within a reasonable limit of size, whole fields of inquiry, including, for example, the involved physical chemistry of silicate melts, have been scantily treated. On the other hand, the geological facts and necessary deductions are put in the foreground. It is hoped that others will find even the theoretical Parts II and III to contain useful records of fact, summarized in the many maps and sections and made further accessible by the use of bibliographical references.

Chapter II gives the reasons for using Rosenbusch's classification of igneous species as the basis for a synthetic study of actual maps and memoirs. New and older averages of the chemical compositions of important rock types are stated. In all, about 700 varieties of igneous rocks are named by petrographers. Families which are nearly identical or are specially related in chemical composition are here grouped as clans. Thus, biotite granite is a species; all granites constitute a family; granites, granite porphyries, rhyolites, etc. form a clan. Although these larger divisions are far from being sharply limited, their recognition facilitates discussion of origins.

Chapter III indicates the present lack of sufficient information regarding the spatial distribution of igneous types. An estimate of their relative quantities in the United States shows some noteworthy contrasts among clans, families, and species. Most of these contrasts are essentially preserved in a still rougher estimate of relative quantities throughout the world. The maximum volumes known to be assumed by separate bodies are also compared, with instructive results.

Chapter IV sketches the relation of igneous types to geological time. The persistence of the gabbro clan in the earth's eruptivity is a prominent fact. All the more important clans are represented in eruptions of both the earliest and latest grand divisions of geological time—the Pre-Cambrian and the Cenozoic. Nevertheless, the relative abundance of some of the chemical types has notably varied with the march of time. Each of the principal modes of eruption, like each of the forms assumed by eruptive bodies, has characterized both Pre-Cambrian and post-Cambrian time.

Chapter V includes some modern data regarding the physics of rocks and magmas—a quantitative statement of properties which are basal to petrological thought.

Chapter VI gives a classification of igneous bodies emplaced by simple injection into the earth's crust. The classification is based on field relations.

Chapter VII describes the leading structural relations of the "subjacent" intrusions (stocks and batholiths), that is, those without visible floors and with no proof that they were emplaced by pure injection. The field facts suggesting that at and near their tops many of these bodies have replaced the country rocks, usually by mechanical incorporation, are emphasized.

Chapter VIII contains a classification of extrusive bodies. The three main categories are fissure eruptions, eruptions of the central type, and deroofing or areal eruptions.

The second principal part of the book, sketching a general theory of the igneous rocks, begins with Chapter IX, which discusses particularly the nature and development of the more superficial layers of the earth's body. In these layers the secrets of igneous action are, for the most part, hidden.

Chapter X introduces the problem of the thermal content of the earth's outer shells. A note on suggested origins of post-Archean magma is followed by sections dealing with the earth's thermal gradients and the origin of the heat, whether an initial endowment of the planet or of later development. Data from cosmogony are briefly considered. It is concluded that the earth probably has a true "crust," overlying a vitreous basic substratum which is highly rigid

against small, periodic stresses and very viscous, but nearly or quite without strength.

Chapter XI is concerned with the first step in any igneous activity since at least the close of the Archean era. This essential process is called "abyssal injection," meaning thereby the mechanical thrusting of vitreous material from the substratum into the solid crust. When the injection is completed in one continuous action, it is called "legato" and is thus distinguished from the "staccato" kind, represented when the intrusive movement is interrupted by pauses. The subject involves debate concerning the conditions for the abyssal fissuring and for the ascent of magmas. These topics lead to a summary of ruling theories of strain in the earth, including the formation of mountain chains.

Chapter XII describes facts and possibilities relating to one cause for the rise of magma into the crust, namely, magmatic stoping. Three kinds are considered. (1) "Piecemeal stoping," the engulfment of many relatively small fragments from roof and walls of an intrusive magma, has clearly been at work in many subjacent bodies and to a limited extent explains their emplacement. (2) Less well demonstrated is "ring-fracture stoping." In this case the magma is supposed to have been initially injected along the sides and top of a more or less circular subterranean block, which then foundered in magma still deeper. (3) Still more speculative, but perhaps much more important than both of the other kinds together, is "major stoping," which is assumed to take place during an orogenic paroxysm, when blocks of rock, nearly or quite as thick as the crust itself, founder in the vitreous substratum. The causes of the shattering of the crust, essential for piecemeal and major stoping, are canvassed and also certain objections that have been urged against the main principle.

Chapter XIII first outlines the hypothesis that under certain conditions blocks of the crust undergo pure melting by the heat of the substratum *in situ* or by the heat of major injections into the crust; it then dwells on the relative importance of the magmatic assimilation of solid rocks. In each case the contrast of Archean and post-Archean conditions is stressed. A genetic classification of the gases engaged in igneous action is interpolated, and the chapter closes with a summary of the preferred theory of the origin of subjacent bodies. Some batholiths are speculatively explained as "major abyssoliths," dikes of basaltic composition being "minor abyssoliths."

Chapter XIV treats of the differentiation of magmas. The units of differentiation are listed, and an abstract of the divergent views on this subject is given. Crystal fractionation is naturally given a prominent place but is not thought to be the only process involved.

A study of injected, subjacent, and extrusive masses proves that differential density has been directly responsible for the separation of many leading species of magmas and rocks. In the present state of knowledge it seems safer to refer to this particular mode of separation as simply "gravitative," rather than to try to state generally and explicitly the nature of the units of differentiation. The origin of "parental" magma and the puzzle of primary banding in igneous rocks, clearly a phenomenon of differentiation, are considered. Finally a summary of the author's whole theory, a genetic classification of igneous species, is offered.

Chapter XV outlines the theory of volcanic action at central vents. Among the topics considered are the localization and opening of the vent; the persistence of its eruptivity for long periods; the alternation of active and dormant stages; the rhythmical character of eruption during an active stage; the origin of the heat in the vent; the rate of loss of heat during activity; the principle of "two-phase convection," which is held to be the chief cause of the transfer of heat from the depths; the systematic changes during the life of a central vent, with respect to explosiveness and the petrographic nature of the lavas; the genetic classification of volcanic gases; the distinction between magmatic and phreatic explosions; and that between "principal" and "subordinate" volcanoes of the central type.

Though Part II is expressly concerned with theory and in many places is intensely speculative, yet many facts of the field are there emphasized. More specific correlation of theory with observed facts is attempted in Part III, a necessarily brief account of the different clans in succession.

In Chapter XVI the more important members of the gabbro clan are discussed. Particular attention is paid to the mafic basalts, the alkali-rich basalts, the quartz diabases and their immediate allies, the norites, the anorthosites, and the spilites.

Chapter XVII begins with a summary of the theory of the Pre-Cambrian granites but is chiefly devoted to an explanation of the post-Archean granites. These are attributed partly to the pure melting of the Sial at great depth and partly to the differentiation of hybrid magmas, formed by the assimilation of solid rocks in basic magma. Though some petrologists believe granitic liquid of post-Archean dates of formation to be residual from the advanced crystallization of basaltic magma, it is improbable that important bodies of post-Archean granite have been developed directly from any kind of primary, uncontaminated liquid.

Chapter XVIII is a short account of the diorite clan. Different modes of origin are suggested. The least speculative of these—

through direct differentiation of some species from basaltic liquid, slightly contaminated by foreign material—is illustrated in the case of the pyroxene andesites. Some diorites and quartz diorites have been explained by various authors as hybrids, syntectic (melted-together) mixtures, and a similar origin is tentatively ascribed to the quartz diorites found on the batholithic scale.

According to reasons expressed in Chapter XIX, granodiorites seem to be differentiates of abyssal syntectics more femic than those normally developed under intracontinental belts of mountain building.

The syenite clan and the feldspathoidal clans are treated, respectively, in Chapters XX and XXI. Including more than half of all the named species, they are believed not to have resulted from pure melting or from the differentiation of any uncontaminated magma, basaltic or other. Field and laboratory observations suggest that nearly all of these rocks are products of reaction between subalkaline magmas and relatively basic sediments or other basic rocks, or else differentiates of mixtures of subalkaline magmas and resurgent gases.

In general, ordinary trachytes and their granular "plutonic" equivalents seem to be differentiates of somewhat modified basaltic liquid. One condition for this origin is the absorption of foreign volatile matter. The more voluminous non-feldspathoidal syenites are attributed, in a similarly speculative way, to the differentiation of basaltic or other subalkaline magmas which have assimilated silica-bearing but relatively basic country rocks, such as shales, slates, phyllites, and perhaps basic volcanics. Moderate superheat and hence the possibility of desilication of the assimilating magmas is assumed, for reasons given in Chapter X. Free quartz is therefore rare or absent in syenites, which otherwise present close analogies in field habit and structural relations with some granites, apparently differentiates of syntectics more acid than those yielding the syenites.

The feldspathoidal clans are explained on the same principle, but for the species here grouped the syntexis in many cases is supposed to be with the carbonate-rich rocks. Some other types may be differentiates of subalkaline magma, particularly the basaltic, contaminated with resurgent volatile matter. Leucitites and their associates may have to be explained by a third mechanism. For lack of appropriate physicochemical data, many problems of detail defy solution.

Chapter XXII sketches outstanding facts and problems connected with the peridotite clan, the anomalous kimberlite, the pyroxenite clan, the hornblendites, certain magmatic ores, and the so-called "carbonatites." These present more questions than answers.

Chapter XXIII reviews the essential reason why the writer of this book has dared to attempt a general theory of the earth's consti-

tution and of igneous action, so far in advance of observational and experimental knowledge. The reason is an apparent paradox; it is held to be good practice in petrology, as it is in physics and chemistry, to fashion a general theory well beyond the limit of known fact so that the theory itself shall stimulate and to some extent guide further investigation in field and laboratory. The principle is illustrated by a summary of the suggestions for future research that come directly from one among the many conceivable theories of the earth.

PART I: LEADING FACTS

CHAPTER II

TYPES OF IGNEOUS ROCKS

Actual mineralogical composition is a natural basis for the classification of rocks and it must always remain the working basis for field classification. Yet the application of this principle encounters difficulties. For the accurate measurement of the proportions of minerals in fine-grained rocks, no direct method has been devised, nor is it likely that such a method is possible. Even if the measuring device were available, the results of its use would be imperfect, since, with few exceptions, each mineral species in rocks is itself of variable composition.

The situation is well recognized by petrographers, who have to regard chemical analysis as essential for any ultimate classification. The world leader Rosenbusch founded his elaborate Mode classification upon mineralogical composition supplemented by constant reference to chemical composition. His system has been that most extensively employed by geologists, and with fair consistency. In general it is used in the following quotation of facts and discussion of those facts. For its description the reader is referred to H. Rosenbusch's "Mikroskopische Physiographie der Massigen Gesteine," 4th edition, Stuttgart, 1907–1908, and "Elemente der Gesteinslehre," 4th edition, revised by A. Osann, Stuttgart, 1923. Here we are not primarily concerned with the merits or future prospects of this system. The important point is that it is the vehicle bearing most of the facts now known about the character and distribution of terrestrial rocks. However, in some important respects the Rosenbusch system will not be followed. For example, the granodiorites are recognized as forming a distinct family, a fact emphasizing the enormous importance of these rocks and their allies in the two Americas and across the Pacific. Again, a thoroughgoing division of igneous rocks into an alkaline series and a subalkaline (calc-alkaline) series is not made, for there appears to be no reason for making so formal and clean-cut a separation.

Average Composition of Igneous-rock Species

Every named type shows some variation in chemical composition. The student of map and memoir should, for many problems, have at hand actual figures showing the most typical chemical composition of the species to which his study is directed. In many cases an analysis

of a single specimen is not so useful as that which could be made from a thorough mixture of specimens of the same variety of rock from all of its outcrops throughout the globe. For obvious reasons such ideal analyses cannot be made. In their stead the investigator of petrological and other world problems may well use the averages computed from existing analyses of single specimens. Such averages approximate rather closely to collective opinion regarding the nature of each corresponding type of rock. They are chemical "center points" in Rosenbusch's system of classification, the one *actually applied* to the terranes of the world—the system which, however modified, has underlain the world's mapping and has thus furnished the raw material on which the petrogenetic theory of this book is founded.

Averages for the more important species have been calculated. The method of computation is essentially like that employed by Washington and Clarke in their respective calculations of the "average composition" of all igneous rocks. In general, only the twelve major oxides were considered; distinctly "inferior" analyses were not included. Each average was computed according to the actual number of determinations. The averages were reduced to 100 per cent. Each was then recalculated to 100 per cent after H_2O (and CO_2) had been subtracted. The results are given in Table 1. The index following it facilitates reference to the different species.

For reasons not far to seek, the table is not complete. The aschistic dike rocks are omitted because of their chemical similarity to the corresponding plutonics. Many varieties are excluded because their analyses are too few to give useful averages.[1]

[1] The immediate sources of the analytical statements used in the computations are as follows:

1. A. Osann, Beiträge zur chemischen Petrographie, 2te Teil, Stuttgart, 1905.
2. H. S. Washington, Chemical Analyses of Igneous Rocks, published from 1884 to 1913, inclusive, Prof. Paper 99, U S. Geol. Survey, 1917.
3. H. Rosenbusch, Elemente der Gesteinslehre, 4th ed. (edited by A. Osann), Stuttgart, 1923.
4. P. J. Holmquist, Studien über die Granite von Schweden, Bull. Geol. Inst. Univ. Upsala, vol. 7, 1906, p. 76.
5. G. W. Tyrrell, Trans. Geol. Soc. Glasgow, vol. 16, part 3, 1917–1918, p. 354; Quart. Jour. Geol. Soc. London, vol. 84, 1928, p. 557.
6. H. S. Washington, Bull. Geol. Soc. America, vol. 33, 1922, p. 797.
7. E. B. Bailey and Others, Tertiary and Post-Tertiary Geology of Mull, etc., Memoir Geol. Survey Scotland, 1924, p. 27.
8. O. A. Broch, Avhand. Norske Videns.-Akad., mat.-naturv. Kl., 1927, No. 9, p. 38.
9. A. Lacroix, Minéralogie de Madagascar, Paris, tome 3, 1923, pp. 49, 63.
10. J. H. L. Vogt, Videns.-Skrifter, Christiania (Oslo), Kl. I, 1924, No. 15, p. 18.
11. Other references given in "Igneous Rocks and Their Origin," 1914, p. 18.

By the inclusion of additional analyses, some of the averages are improvements on the corresponding averages given in "Igneous Rocks and Their Origin." These are indicated by *asterisks* attached to the rock names in Table 1. New averages are similarly indicated by *double asterisks.*

TABLE 1.—AVERAGE COMPOSITIONS
(Totals reduced to 100.00)

	Plutonic				Effusive			
	1	2	3	4	5	6	7	8
	Pre-Cambrian granite (world)	Pre-Cambrian granite of Sweden	Post-Cambrian granite	Granite of all periods*	Rhyolite, including 24 liparites*	Liparite	Rhyolite, as named by authors*	Quartz porphyry
Number of analyses	47	114	184	546	126	24	102	50
SiO_2	71.06	69 81	69 73	70 18	72.80	72.90	72 77	72 36
TiO_2	.48	.54	.34	.39	.33	.48	.29	.33
Al_2O_3	14 10	13 76	14 98	14.47	13 49	14.18	13.33	14.17
Fe_2O_3	1.46	2.17	1 62	1 57	1.45	1.65	1.40	1 55
FeO	1 63	1.87	1.66	1.78	88	.31	1.02	1.01
MnO	.18	.26	.11	.12	.08	.13	.07	.09
MgO	59	84	1 08	.88	.38	.40	.38	.52
CaO	1.97†	2.20	2.20‡	1 99	1.20	1.13	1.22	1 38
Na_2O	3 24	3.17	3 28	3 48	3.38	3.54	3.34	2 85
K_2O	4.50	4 38	3.95	4.11	4.46	3.94	4.58	4 56
H_2O	.69	.74	.78	84	1.47	1.33	1.50	1.09
P_2O_5	.10	26	.27	19	.08	.01	.10	.09
Calculated as water free								
SiO_2	71 56	70.33	70.28	70.77	73.89	73 89	73.88	73.16
TiO_2	.48	.54	.34	.39	33	.49	.29	.33
Al_2O_3	14.20	13.86	15.10	14 59	13.69	14 37	13.54	14 33
Fe_2O_3	1.47	2.19	1.63	1.58	1.47	1.67	1.42	1.57
FeO	1 65	1.89	1 67	1.79	.90	.31	1.04	1 02
MnO	.18	.26	.11	.12	.08	.13	.07	.09
MgO	.59	.85	1.09	.89	.38	.41	.38	.53
CaO	1.98†	2.22	2.22‡	2.01	1.22	1.14	1.24	1 39
Na_2O	3.26	3.19	3.31	3.52	3.43	3 59	3.39	2.88
K_2O	4.53	4.41	3.98	4.15	4.53	3.99	4.65	4.61
P_2O_5	.10	.26	.27	.19	.08	.01	.10	.09

† Includes 0.08 per cent BaO and 0.01 per cent SrO.
‡ Includes 0.06 per cent BaO and 0.02 per cent SrO.

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	Plutonic		Effusive		
	9	10	11	12	13
	"Subalkaline" granite	"Alkaline" granite	Comendite*	Quartz keratophyre	Pantellerite
Number of analyses	20	12	14	13	12
SiO_2	69 21	73.30	73.51	75 45	68 63
TiO_2	41	.11	29	17	35
Al_2O_3	14.41	12 33	11 43	13.11	10 30
Fe_2O_3	1 98	2.58	2 97	1.14	5 60
FeO	1 67	1.28	1 08	.66	2 61
MnO	.12	.02	.04	.29	21
MgO	1 15	.26	.16	.34	.37
CaO	2 19	.46	.28	.83	1.07
Na_2O	3.48	4.55	4 65	5.88	6 14
K_2O	4 23	4 20	4.53	1 26	4 17
H_2O	.85	.86	1.02	.69	.53
P_2O_5	.30	.05	.04	.18	.02
Calculated as water free					
SiO_2	69 82	73 94	74 27	75.98	69 00
TiO_2	.41	.11	.29	.17	.35
Al_2O_3	14 53	12.44	11 55	13 20	10 36
Fe_2O_3	2.00	2 60	3 00	1.15	5 63
FeO	1.68	1 29	1.09	.66	2.62
MnO	.12	.02	.04	29	.21
MgO	1.16	.26	.16	.34	.37
CaO	2 21	46	.28	.84	1.08
Na_2O	3 51	4.59	4.70	5.92	6.17
K_2O	4.26	4.24	4.58	1.27	4.19
P_2O_5	.30	05	.04	.18	.02

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	Plutonic					Effusive	
	14	15	16	17	18	19	20
	"Subalkalne" hornblende syenite	"Subalkalne" mica syenite	"Subalkaline" augite syenite	"Subalkaline" syenite, all types	All syenite, including five analyses of "alkaline" types	Trachytes, as named by authors	"Subalkaline" trachyte
Number of analyses	7	2	2	11	50	48	10
SiO_2	60.79	59 25	51 59	58.65	60 19	60.68	63.91
TiO_2	.80	.79	61	.86	67	.38	.59
Al_2O_2	16 10	15.28	18 77	16 38	16 28	17 74	15.88
Fe_2O_3	3 21	2 59	6 11	3.65	2.74	2 64	3.22
FeO	2 92	3.47	3 26	3.09	3 28	2.62	2 23
MnO	.11	...	.24	.15	.14	.06	.01
MgO	2 20	5 07	4 11	3 06	2.49	1.12	1 14
CaO	3.87	3.68	7 35	4.45	4 30	3 09	2.81
Na_2O	3 37	3 10	4 35	3 48	3.98	4 43	3 08
K_2O	5 43	4.41	2.99	4.79	4.49	5.74	5.80
H_2O	.90	2 06	.26	1 13	1.16	1.26	1.28
P_2O_5	.30	.30	36	.31	28	.24	.05
	Calculated as water free						
SiO_2	61 34	60.49	51 72	59.32	60 90	61.46	64.74
TiO_2	81	80	.61	.87	.68	38	60
Al_2O_3	16.25	15.60	18 82	16 56	16 47	17 97	16.09
Fe_2O_3	3 24	2.65	6 13	3 69	2.77	2 67	3 26
FeO	2.95	3 55	3 27	3.13	3 32	2.66	2.26
MnO	.11	....	.24	.15	.14	.06	.01
MgO	2.22	5.17	4.12	3.10	2.52	1.13	1 15
CaO	3 90	3 76	7 37	4.50	4.35	3.13	2 85
Na_2O	3 40	3.17	4.36	3 52	4 03	4.49	3 12
K_2O	5 48	4.50	3.00	4.85	4.54	5 81	5 87
P_2O_5	.30	.31	36	31	28	24	.05

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	Plutonic					Effusive	
	21	22	23	24	25	26	27
	Nordmarkite	Pulaskite*	Akerite	Umptekite	Average "alkaline" syenite (columns 21–24 inclusive)*	"Alkaline" trachyte	Keratophyre
Number of analyses	7	12	8	5	32	19	7
SiO_2	64 36	61.58	61 96	60.01	62 00	62.63	61 51
TiO_2	45	.33	99	.64	57	62	45
Al_2O_3 . ..	16 81	18 37	17 07	16 65	17 44	17 06	17 37
Fe_2O_3	1 08	2.28	2 35	2 41	2 06	3 01	1 92
FeO	2.71	1.71	3 37	3 85	2.68	1.98	3.35
MnO. . ..	.15	.11	.09	18	.12	13	01
MgO.. .	72	.69	1 38	97	91	.63	1.26
CaO.. ...	1 55	1 77	3 41	2 62	2.26	1.51	1 08
Na_2O.. ...	5 76	6 45	4 65	6 53	5 86	6.26	5.23
K_2O	5.62	5 70	3 80	5 47	5.17	5.37	5 29
H_2O..	.70	80	.93	.50	.76	.71	2.45
P_2O_5........	.09	.21	.....	.17	.17	.09	.08
Calculated as water free							
SiO_2	64 81	62.08	62 55	60.32	62.47	63 09	63 06
TiO_2........	.45	33	1 00	.64	.59	.62	46
Al_2O_3	16.93	18.52	17.23	16.74	17.56	17.18	17.81
Fe_2O_3........	1.09	2 30	2 37	2 42	2.08	3.03	1.97
FeO........	2.73	1.73	3 40	3.87	2.70	2 00	3.43
MnO........	.15	11	09	.18	12	.13	.01
MgO........	.73	69	1.39	.97	.92	.63	1.29
CaO........	1 56	1 79	3 44	2 63	2.28	1.52	1.11
Na_2O........	5.80	6 50	4 69	6 56	5.90	6.30	5.36
K_2O	5 66	5 74	3 84	5 50	5.21	5.41	5.42
P_2O_5..	.09	21	.....	.17	.17	.09	.08

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	Plutonic	Effusive	Plutonic	Effusive		
	28	29	30	31	32	33
	Laurvikite	Rhomb-porphyry	Monzonite*	Latite	Trachyandesite**	Quartz latite**
Number of analyses	3	7	27	10	12	12
SiO_2	57 45	56 36	56 12	57 65	57.84	62.43
TiO_2	....	48	1 10	1 00	1.11	.85
Al_2O_3	21 11	20 10	16 96	16 68	17.24	16.15
Fe_2O_3	2 89	2 86	2.93	2.29	3.97	4.04
FeO	2.39	2 01	4.01	4 07	3.18	1.20
MnO	.	01	.16	10	.05	.09
MgO	1 06	1 15	3 27	3 22	1 25	1.74
CaO	4 10	2.73	6 50	5 74†	4.20	4.24
Na_2O	5 80	7 65	3 67	3 59	5 67	3.34
K_2O	3 87	4 97	3 76	4.39	3.62	3.75
H_2O	70	1 20	1 05	91‡	1 30	1.90
P_2O_5	54	48	47	.36	57	27
Calculated as water free						
SiO_2	57.85	57.06	56.72	58.18	58.60	63 64
TiO_2	.... .	.48	1.11	1.01	1.12	.86
Al_2O_3	21.26	20 35	17.14	16.84	17 47	16.47
Fe_2O_3	2 91	2.90	2.96	2 31	4.02	4.12
FeO	2.41	2.04	4.05	4.11	3.22	1.22
MnO	.....	.01	.16	.10	.05	.09
MgO	1.07	1.16	3.30	3.25	1.26	1.78
CaO	4.13	2.76	6.57	5.79‡	4.26	4.32
Na_2O	5.93	7.74	3.71	3 62	5.75	3.41
K_2O	3.90	5.01	3 80	4 43	3.67	3.82
P_2O_5	.54	.49	.48	.36	.58	.27

† Includes 0.16 per cent BaO and 0.07 per cent SrO.
‡ Includes 0.14 per cent CO_2.

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	Plutonic							Effusive
	34	35	36	37	38	39	40	41
	Canadite**	Urtite	Malignite	Foyaite	Lujavrite*	Laurdalite	Nephelite syenite	Phonolite
Number of analyses	7	3	4	10	12	3	43	25
SiO_2 ...	49 07	45.61	50 34	56 11	53 78	54 36	54.63	57 45
TiO_2..	.63	....	.34	.45	1 02	1 30	86	41
Al_2O_3 ...	21.71	27 76	14 75	21.33	16 33	19 99	19.89	20 60
Fe_2O_3.	2 88	3.67	4 18	1 87	6 95	2 79	3 37	2 35
FeO.	5 90	.50	2.75	1.47	3 01	2 58	2 20	1.03
MnO	.17	.15	.11	.05	.55	.18	.35	.13
MgO...	1.51	.19	4 23	55	.62	1 72	.87	.30
CaO........	4.80	1.73	10 43	1.72	1 70	2 96	2.51	1.50
Na_2O . ..	8 46	16.25	5.27	8 48	10 45	8 28	8.26	8 84
K_2O	2 98	3.72	5 21	6.46	3.78	4 98	5 46	5 23
H_2O. . .	1.50	.42	1 20	1 50	1.80	22	1.35	2 04
P_2O_5.. . ..	39	.. ..	1 19	.01	01	64	25	.12
Calculated as water free								
SiO_2	49 82	45 80	50 95	56 96	54 77	54 48	55 38	58 65
TiO_2	64	. .	35	.46	1 04	1 30	87	.42
Al_2O_3	22 04	27 88	14.93	21 65	16 63	20 03	20 16	21.03
Fe_2O_3.	2.92	3 68	4 23	1 90	7 08	2 80	3 42	2 40
FeO...... ..	5 99	.50	2 78	1.49	3.06	2.59	2 23	1 05
MnO.	17	.15	.11	.05	.56	.18	35	.13
MgO	1 53	.19	4 28	.56	63	1.72	.88	.31
CaO.	4 87	1 74	10 56	1 75	1 73	2.97	2 54	1.53
Na_2O ..	8 59	16.32	5 33	8.61	10 64	8 30	8.38	9 02
K_2O . .	3 03	3.74	5 27	6 56	3 85	4 99	5 54	5 34
P_2O_5	40	.	1 21	.01	01	64	25	12

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	Plutonic				Effusive
	42	43	44	45	46
	Quartz diorite*	Tonalite*	Quartz mon-zonite	Granodiorite*	Dacite*
Number of analyses	55	10	20	40	90
SiO_2	61 59	61.32	66.64	65.01	65.68
TiO_2	66	.23	.50	.57	.57
Al_2O_3	16 21	16 95	15 57	15.94	16 25
Fe_2O_3	2 54	2.39	1.91	1.74	2.38
FeO	3 77	4.29	1 94	2.65	1 90
MnO	10	.05	.06	.07	.06
MgO	2 80	2.84	1.41	1.91	1.41
CaO	5 38	5.56	3.50	4.42	3 46
Na_2O	3 37	2 62	3.41	3.70	3.97
K_2O	2 10	2 20	3 72	2.75	2.67
H_2O	1.22	1.22	1.15	1.04	1 50
P_2O_5	26	.33	19	.20	.15
Calculated as water free					
SiO_2	62 35	62 08	67.41	65 69	66.68
TiO_2	.67	23	.51	.57	.58
Al_2O_3	16 41	17 16	15.76	16.11	16.50
Fe_2O_3	2 57	2 42	1.93	1.76	2.41
FeO	3 82	4.35	1.96	2.68	1.93
MnO	.10	05	.06	.07	.06
MgO	2 83	2.87	1.43	1.93	1.44
CaO	5 45	5 63	3.54	4.47	3.51
Na_2O	3.41	2.65	3.45	3.74	4.03
K_2O	2 13	2 23	3 76	2.78	2.71
P_2O_5	26	33	.19	.20	.15

TABLE 1.—AVERAGE COMPOSITIONS —(*Continued*)

	Plutonic		Effusive				
	47	48	49	50	51	52	53
	Diorite, including 55 quartz diorites	Diorite, excluding quartz diorite	All andesite	Augite andesite	Hypersthene andesite	Hornblende (amphibole) andesite	Mica andesite
Number of analyses	125	70	87	33	20	24	10
SiO_2	58 90	56.77	59 59	57.50	59 48	61.12	62 25
TiO_2	76	.84	77	79	.48	42	1.65
Al_2O_3	16 47	16.67	17.31	17 33	17.38	17 65	16.10
Fe_2O_3	2.89	3.16	3.33	3.78	2.96	2 89	3.62
FeO	4.04	4.40	3 13	3 62	3 67	2.40	2 20
MnO	.12	.13	18	.22	15	.15	21
MgO	3 57	4.17	2.75	2.86	3 28	2.44	2 03
CaO	6.14	6 74	5 80	5.83	6 61	5 80	4.05
Na_2O	3.46	3 39	3 58	3 53	3.41	3 83	3.55
K_2O	2 11	2 12	2 04	2 36	1.64	1 72	2.44
H_2O	1.27	1.36	1.26	1 88	74	1 43	1 50
P_2O_5	27	25	26	30	20	15	40
Calculated as water free							
SiO_2	59 67	57 56	60 35	58.65	59 92	62 01	63 20
TiO_2	77	.85	.78	80	.48	43	1.67
Al_2O_3	16 68	16 90	17.54	17 67	17 51	17 91	16.35
Fe_2O_3	2.93	3 20	3 37	3 85	2 98	2 93	3.67
FeO	4 09	4.46	3.17	3.69	3.70	2.44	2.23
MnO	.12	.13	18	.22	.15	.15	.21
MgO	3 62	4 23	2.78	2 90	3 31	2.48	2 06
CaO	6.22	6.83	5.87	5 92	6.66	5 88	4.11
Na_2O	3.50	3 44	3 63	3.60	3.44	3.88	3.61
K_2O	2 13	2.15	2.07	2 40	1 65	1.74	2 48
P_2O_5	27	.25	26	30	20	.15	.41

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	Plutonic				Effusive			
	54	**55**	**56**	**57**	**58**	**59**	**60**	**61**
	Norite, excluding olivine norite*	Gabbro, excluding olivine gabbro	Olivine gabbro	All gabbro	All basalt[1]	Basalt, as named by authors, with anamesite, tachylite, etc.	Plateau basalt[2]	Melaphyre
Number of analyses	24	24	17	41	198	161	43	11
SiO_2	50.39	49 50	46.49	48.24	49 06	48 78	48.80	50.60
TiO_2	1 13	.84	1.17	97	1.36	1 39	2.19	.68
Al_2O_3	16.06	18.00	17.73	17 88	15.70	15.85	13.98	17.40
Fe_2O_3	2.43	2 80	3.66	3.16	5.38	5 37	3.59	4.57
FeO	7.86	5.80	6.17	5.95	6.37	6.34	9.78	6.29
MnO	.17	.12	.17	.13	.31	.29	.17	.46
MgO	8.37	6.62	8.86	7.51	6.17	6.03	6.70	4.89
CaO	9.20	10.64	11.48	10.99	8.95	8.91	9.38	8.09
Na_2O	2.61	2.82	2.16	2.55	3.11	3.18	2.59	3.23
K_2O	.79	.98	.78	89	1.52	1.63	.69	1.76
H_2O	.79	1.60	1 04	1.45	1.62	1 76	1.80	1.83
P_2O_5	.20	.28	.29	28	.45	.47	.33	.20
Calculated as water free								
SiO_2	50.79	50.31	46 97	48 95	49.87	49.65	49.70	51.54
TiO_2	1 14	.85	1.18	.98	1.38	1.41	2.23	.69
Al_2O_3	16 19	18.30	17 92	18 15	15.96	16.13	14.24	17.73
Fe_2O_3	2.45	2.85	3 70	3.21	5.47	5.47	3.66	4.66
FeO	7.92	5.89	6.24	6.04	6.47	6.45	9.96	6.41
MnO	.17	.12	.17	.13	.32	.30	.17	.47
MgO	8 44	6.73	8.96	7 62	6.27	6.14	6.82	4.99
CaO	9.27	10.81	11.60	11 15	9.09	9.07	9.55	8.24
Na_2O	2 63	2 86	2 18	2 59	3 16	3.24	2.64	3.29
K_2O	.80	1.00	.79	.90	1.55	1.66	.70	1.78
P_2O_5	.20	28	29	28	46	.48	.33	.20

[1] Including 161 basalts, 17 olivine diabases, 11 melaphyres, and 9 dolerites.

[2] Average of 3 Oregonian, 8 New Jerseyan, 1 Patagonian, 1 Karroo, 8 Deccan, 4 Icelandic, 2 Faroe Island, 3 Greenland, 6 Spitzbergen, 2 Franz Joseph Land, 5 Scottish Island

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	62	63	64	65	66	67	68	69
	Olivine norite*	Quartz gabbro**	Anorthosite	Olivine diabase*	Diabase*	Dolerite*	Quartz diabase**	Quartz basalt**
Number of analyses	3	6	12	12	90	20	12	14
SiO_2	48.78	54 39	50 40	48 54	50.48	49.94	52.34	55 46
TiO_2	1.48	1 29	.15	1 31	1.45	1.57	1 82	.88
Al_2O_3	18.04	16 72	28.30	15 24	15.34	14.50	13.70	16 85
Fe_2O_3	1.16	2.49	1.06	3 06	3.84	3.74	5.05	2 13
FeO	8.94	7 15	1.12	8 88	7.78	8.01	8.78	4 86
MnO	.20	20	.05	21	.20	.33	.23	.22
MgO	8.07	4 15	1.25	8 08	5.79	6.93	4.72	6 31
CaO	8.92	6 68	12 46	9 38	8.94	9.71	8.03	7 86
Na_2O	2.56	3 15	3.67	2 69	3.07	2.65	2.60	3 30
K_2O	.91	1 58	.74	98	.97	.97	1.17	1.40
H_2O	.69	1.85	.75	1 35	1.89	1.28	1.56	.58
P_2O_5	.25	.35	.05	28	.25	.37	....	15
Calculated as water free								
SiO_2	49.12	55 42	50.78	49 21	51.45	50 59	53.17	55.78
TiO_2	1.49	1 31	.15	1.33	1.48	1 59	1.85	.89
Al_2O_3	18.17	17 04	28 51	15 45	15 64	14 68	13.92	16 95
Fe_2O_3	1.17	2 54	1.07	3 10	3 91	3 79	5.13	2 14
FeO	9 00	7 28	1 13	9 00	7.93	8.12	8.92	4.89
MnO	.20	21	05	21	.21	.32	.23	22
MgO	8.12	4 22	1.26	8 19	5.90	7 04	4.79	6.35
CaO	8.98	6 80	12 55	9 51	9.11	9.84	8.16	7.90
Na_2O	2 58	3 21	3 70	2 73	3.13	2 68	2.64	3.32
K_2O	92	1 61	75	99	98	98	1 19	1 41
P_2O_5	25	36	05	28	26	37	.....	15

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	70	71	72	73
	Picrite	Oceanite[1]**	Ankaramite**	Ankaratrite**
Number of analyses	14	10	4	24
SiO_2	41 30	45 6	43.82	39 49
TiO_2	.81	1 7	3 32	3.23
Al_2O_3	9 43	8 3	8 81	9 71
Fe_2O_3	5 30	2 3	3 08	4 53
FeO	8 86	10.2	8 01	7.74
MnO	.29	1		
MgO	19 94	21 7	15 50	14 85
CaO	8 01	7.5	13 50	14.17
Na_2O	1 20	1.3	1 51	2.31
K_2O	39	.4	.87	1.34
H_2O	4 27	.6	1 17	1.99
P_2O_5	20	.3	.41	.64
	Calculated as water free			
SiO_2	43 14	45.9	44 35	40 30
TiO_2	85	1.7	3.36	3.29
Al_2O_3	9 85	8.3	8 91	9 91
Fe_2O_3	5.54	2.3	3 11	4 62
FeO	9 26	10.3	8 10	7.90
MnO	.30	1		
MgO	20.83	21 9	15 68	15.15
CaO	8.37	7 5	13.66	14.46
Na_2O	1.25	1 3	1.53	2.36
K_2O	.40	4	.88	1.36
P_2O_5	.21	3	.42	65

[1] Average computed by G W Tyrrell, The Principles of Petrology, 1926, p 131

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	74	75	76	77	78	79	80	81
	Cortlandtite**	Amphibole peridotite	Wehrlite	Harzburgite (saxonite)*	Lherzolite*	Dunite*	Mica peridotite*	Kimberlite†**
Number of analyses	6	7	5	8	13	10	4	10
SiO_2	44 45	40.91	45 07	40 65	43 95	40 49	33.94	34.73
TiO_2	1 21	65	64	.11	.10	.02	4 95	1 62
Al_2O_3	6 40	5.00	5 75	1 25	4 82	86	10.28	2.88
Fe_2O_3	2 91	4 64	3 43	2 53	2.20	2.84	4.59	6.10
FeO	7 89	7 97	9 53	6 15	6.34	5 54	11.12	3.13
MnO	17	.07	26	18	19	.16	.16	
MgO	25 05	30 82	22 88	42 36	36 81	46 32	20.45	31.41
CaO	8 52	4.41	7.48	1.29	3 57	.70	5.35	5.79
Na_2O	.92	58	1 14	29	63	.10	48	.33
K_2O	54	36	57	.13	21	04	4.90	1.17
H_2O	1 83	4.56	3 10	5 02	1.08	2 88	2.96	9.20
P_2O_5	11	03	15	04	10	.05	.82	3.64‡
Calculated as water free								
SiO_2	45.29	42 87	46.51	42.81	44.44	41 69	34.98	38.25
TiO_2	1 23	68	.66	12	.10	.02	5.10	1.78
Al_2O_3	6.52	5 25	5.93	1 31	4 87	.89	10.59	3.17
Fe_2O_3	2 96	4 87	3.54	2.66	2 22	2.93	4.73	6.72
FeO	8.04	8 34	9.84	6.48	6.41	5.70	11.46	3.45
MnO	17	07	27	19	.19	.16	.17	
MgO	25 51	32 30	23 61	44.61	37.21	47.70	21.07	34.59
CaO	8.68	4.63	7 72	1 36	3.61	.72	5.51	6.38
Na_2O	94	59	1.17	.29	.64	.10	.50	.36
K_2O	55	.37	59	.13	.21	.04	5.05	1.29
P_2O_5	11	03	.16	04	.10	.05	.84	4.01§

† Including four "basaltic kimberlites."
‡ Number includes 1 06 per cent P_2O_5 and 2.58 per cent CO_2.
§ Number includes 1 17 per cent P_2O_5 and 2.84 per cent CO_2.

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	82	83	84	85	86	87	88	89
	Hornblendite**	Websterite*	Bronzitite**	Diallagite**	Augitite	Limburgite	Bekinkinite	Ijolite
Number of analyses	11	12	5	14	6	14	2	6
SiO_2	42.80	52 33	54 63	46.93	42 25	41 25	41 70	42 81
TiO_2.	1 62	.10	36	97	2 52	1 59	2 70	1.56
Al_2O_3.	10 55	3 54	2.39	6 37	16.26	12.03	14.50	18 95
Fe_2O_3.	6.62	2 61	1.71	4.08	8 43	5.65	5 13	3 86
FeO.	9.16	5.19	7.07	10.85	5 46	7.29	7.09	4.84
MnO.	.24	.15	.14	20	. . . .	.54	. . .	.19
MgO.	12.48	23.92	30.30	12 13	5 49	11.22	9.26	3 16
CaO.	11.67	10.29	2.20	16 03	9 75	11.88	12 20	10.47
Na_2O.	1.89	.43	.45	.82	4.45	3.40	3 59	9.63
K_2O.	1.00	.35	.11	.49	1.92	1.30	1.18	2.26
H_2O.	1 73	1 03	.52	1.01	2 43	3.20	1 80	.85
P_2O_5.	.24	06	.12	.12	1.04	.65	.85	1.42
				Calculated as water free				
SiO_2.	43.56	52.87	54 91	47.41	43 30	42 62	42.47	43.18
TiO_2.	1.65	.10	.36	98	2.58	1 65	2 75	1.56
Al_2O_3.	10.73	3.58	2.40	6.43	16 67	12.43	14 77	19.12
Fe_2O_3.	6.73	2.64	1.72	4.12	8 64	5 84	5.22	3.89
FeO.	9.33	5.24	7.11	10.96	5.59	7.53	7.22	4 88
MnO.	.24	.15	.14	.20	. . . .	.56	. . . .	.19
MgO.	12.70	24.17	30.47	12.25	5 63	11.60	9 42	3 19
CaO.	11.88	10.40	2.21	16.20	9.99	12.28	12 42	10.56
Na_2O.	1.92	.44	.45	.83	4.56	3.48	3.66	9 72
K_2O.	1.02	.35	.11	.50	1.97	1.34	1.20	2.28
P_2O_5.	.24	.06	.12	.12	1.07	67	.87	1.43

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	Plutonic				Effusive			
	90	91	92	93	94	95	96	97
	Teschenite**	Theralite	Essexite-gabbro**	Essexite	Trachydolerite	Crinanite**	Analcite basalt**	Mugearite**
Number of analyses	12	6	6	20	34	6	15	4
SiO_2	45 52	45 61	46 79	48 64	49 20	44 38	44 84	49 86
TiO_2	2 07	1 96	2 94	1 86	1 68	1 98	2 56	2 12
Al_2O_3	16 08	14 35	16 77	17 96	16 65	15 46	14 04	14 42
Fe_2O_3	4 18	6 17	3.21	4 31	4 76	3 27	3.95	5 65
FeO	6 37	4 03	7 24	5 58	5 36	10 17	6 69	7.49
MnO	27	19		19	55	26	15	39
MgO	4 85	6.05	5 83	4.00	4 43	7 27	8 96	3 43
CaO	8.34	9.49	10 17	8 89	7.74	9 24	9.18	6 80
Na_2O	4 63	5.12	3 52	4 30	4 54	3.31	3.73	4.21
K_2O	2 09	3 69	1.89	2 28	3 19	90	1 76	1 67
H_2O	4 92	2.60	1 32	1 34	1 30	3 48	3 44	3.09
P_2O_5	68	.74	32	.65	.60	28	.70	.87
Calculated as water free								
SiO_2	47 88	46 83	47 42	49 31	49 85	45 98	46 44	51.45
TiO_2	2 18	1.98	2.97	1 88	1 70	2 06	2.65	2.19
Al_2O_3	16.91	14 73	17 00	18 20	16 88	16 02	14.54	14 88
Fe_2O_3	4 39	6 34	3 25	4 37	4 82	3 39	4.09	5.82
FeO	6 70	4.14	7 34	5 66	5 43	10 53	6.93	7.73
MnO	28	19	.	19	.56	26	.16	.40
MgO	5.10	6 22	5 91	4 05	4.48	7.54	9.28	3.56
CaO	8 78	9.75	10 31	9.01	7 84	9 57	9.51	7.02
Na_2O	4 87	5 27	3 57	4 36	4.60	3.43	3.86	4.34
K_2O	2 20	3 79	1 91	2 31	3 23	.93	1.82	1.72
P_2O_5	71	76	.32	66	61	.29	.72	.89

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	98	99	100	101	102	103	104
	Shonkinite	All tephrite	All basanite*	Nephelite tephrite	Leucite tephrite	Nephelite basanite	Leucite basanite*
Number of analyses	6	24	26	4	20	16	10
SiO_2	48.66	49 14	44 64	46.91	49 90	44.20	45 55
TiO_2	.97	1 00	1 95	1.81	16	1 64	2.33
Al_2O_3	12.36	16 57	15 35	15.25	16 94	15.64	14 97
Fe_2O_3	3.08	3 65	4.51	7 70	3.02	4.35	4.77
FeO	5.86	6.68	6.33	4.06	7.15	6.14	6.64
MnO	13	30	.46	1 43	23	.19	.61
MgO	8.09	3 98	7 92	2.95	4 22	8.89	6.41
CaO	10 46†	9 88	9 88	9.36	10 04	9 74	10.16
Na_2O	2 71	2 57	3 54	4.25	2 24	4.03	2.76
K_2O	5.15	3 39	2 67	2.63	3 57	1 83	4.04
H_2O	1.46	2 00	2 18	2.51	1 74	2 67	1.61
P_2O_5	1.07	84	57	1.14	.79	.68	.15
Calculated as water free							
SiO_2	49.38	50 15	45 64	48.12	50.79	45 41	46.29
TiO_2	98	1 02	1.99	1.86	.16	1 68	2.37
Al_2O_3	12.55	16 90	15 69	15.65	17 24	16 07	15.22
Fe_2O_3	3.12	3 72	4 61	7 89	3.07	4 47	4.85
FeO	5.95	6 82	6 47	4.16	7 28	6 31	6.75
MnO	.13	31	47	1.47	23	.20	.15
MgO	8 21	4 06	8 10	3.02	4 30	9 13	6.51
CaO	10.62‡	10 08	10 10	9.60	10 22	10 01	10.33
Na_2O	2.75	2 62	3 62	4.36	2 28	4 14	2.80
K_2O	5 23	3 46	2.73	2.70	3 63	1 88	4.11
P_2O_5	1 08	86	58	1.17	80	70	.62

† Includes 0.40 per cent BaO and 0.09 per cent SrO.

‡ Includes 0.41 per cent BaO and 0.09 per cent SrO.

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	105	106	107	108
	Fergusite*	Missourite	Leucite basalt*	Leucitite*
Number of analyses	2	2	12	9
SiO_2	48 97	44 27	46.18	46 90
TiO_2	81	1 37	2.13	1 22
Al_2O_3	17 48	10 73	12 74	16 33
Fe_2O_3	3 61	3.63	5 27	4 22
FeO	3 43	5 87	5 06	4 14
MnO	.10	06	.19	11
MgO	5 43	13 05	8 36	5.03
CaO	7 77	11 46†	8 16	9 72
Na_2O	2.50	1 07	2 36	2.75
K_2O	7.18	4 43	6 18	7.58
H_2O	2 04	3 23	2 60	1.50
P_2O_5	68	83	.77	50
Calculated as water free				
SiO_2	49 99	45 75	47 41	47.61
TiO_2	83	1 41	2 19	1 24
Al_2O_3	17.85	11 09	13 09	16 58
Fe_2O_3	3 69	3 75	5 41	4 28
FeO	3 50	6 07	5 20	4.20
MnO	.10	06	.19	11
MgO	5.54	13 49	8 58	5 11
CaO	7.93	11.85‡	8 38	9.87
Na_2O	2.55	1 10	2 42	2 79
K_2O	7 33	4.57	6 34	7 70
P_2O_5	69	.86	79	51

† Includes 0 48 per cent BaO and 0 18 per cent SrO.
‡ Includes 0.50 per cent BaO and 0 19 per cent SrO.

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	109	110	111	112	113	114	115
	Leucite phon	Leucitophyre	Nephelinite	Nephelite basalt	Melilite-nephelite basalt	Melilite basalt	Hauynophyre**
Number of analyses	4	8	9	26	5	5	10
SiO_2	54 89	49.83	41.17	39.87	37 56	35.72	43.91
TiO_2	. .	.71	1.35	1.50	2.66	4.78	2.74
Al_2O_3 ...	21.28	19.00	16.83	13.58	10.08	9.56	17.17
Fe_2O_3 .	3.04	3 17	7.61	6.71	6.82	5.41	4.15
FeO	1.49	3.59	6.64	6.43	5.94	6.55	5.12
MnO.......	.01	.17	.16	.21	.06	.....	.11
MgO	.66	1.79	3.72	10 46	15.32	15.46	3.33
CaO	2.31	5.69	10.12	12.36	13.82	14 20	8.83
Na_2O ...	5 62	7.19	6.45	3 85	3 11	3.35	6.17
K_2O	8 39	6.15	2.49	1 87	1.53	1 67	3 52
H_2O . ..	2.31	1.93	2 42	2 22†	2.52	2 67	4.25‡
P_2O_5 . .	....	.78	1 04	94	.58	.63	.70
Calculated as water free							
SiO_2. .. .	56.19	50 82	42.19	40.77	38 54	36.70	45 15
TiO_2.	....	.72	1 38	1 53	2.73	4.91	2.80
Al_2O_3.	21 78	19.38	17.25	13 88	10.35	9.82	17 65
Fe_2O_3	3 11	3.23	7.79	6.86	7.00	5.55	4.26
FeO	1 53	3.66	6.81	6.57	6 09	6.73	5.27
MnO	.01	.17	.17	.21	.06	.....	.11
MgO.	.68	1.83	3.81	10.73	15.70	15.89	3.43
CaO..... ..	2.36	5.80	10.37	12.65	14.17	14.59	9.08
Na_2O ...	5 75	7.33	6.61	3.94	3.19	3.44	6.35
K_2O.......	8.59	6 27	2.55	1 90	1.57	1.72	3.62
P_2O_5.... ...	. .	.79	1.07	96	.60	.65	.72

† Includes 0.29 per cent CO_2.

‡ Includes 1.25 per cent SO_3 and 0.27 per cent Cl; the corresponding percentages, 1.28 and 0.28, to be added in water-free column.

TABLE 1 —AVERAGE COMPOSITIONS.—(*Continued*)

	116	117	118	119	120	121	122
	Alaskite	Diorite of Electric Peak	Rhyolite of Yellowstone Park	Banakite	Shoshonite	Absarokite	Leucite absarokite
Number of analyses	3	10	10	4	8	5	2
SiO_2	76.47	62 21	74 04	52.04	53 56	50.11	47 45
TiO_2	.07	60	.18	.76	82	96	.81
Al_2O_3	13.03	16 45	13.19	17 65	17.88	13 04	11.43
Fe_2O_3	1.04	2 53	1.35	4 66	4 51	4 58	3.22
FeO		2.89	1.01	2 75	3 05	3 94	5 78
MnO	.01	.02	.04	.13	07	.11	12
MgO	.06	3 32	.32	3 33	3 62	9.27	14.60
CaO	.45	4 96	1 19	5 11	6 45	7 63	8 18
Na_2O	3.53	3 88†	3 88	4 10	3 41	1.94	2.32
K_2O	4.81	2.21	3 75	5 03	3 76	4.15	2 99
H_2O	.52	.80‡	1 02§	3 74	2.32	3.58	2.50
P_2O_5	01	13	03	70	55	69	.60
Calculated as water free							
SiO_2	76 87	62 71	74 80	54 06	54.84	51 97	48.67
TiO_2	07	60	18	.79	.84	1.00	.83
Al_2O_3	13 10	16.58	13 33	18.34	18.31	13.52	11.73
Fe_2O_3	1 05	2 55	1.37	4.84	4.62	4.74	3.30
FeO		2 92	1.02	2.85	3.12	4.08	5.93
MnO	.01	.02	04	.14	.07	.12	.12
MgO	06	3.35	.32	3.46	3.70	9.62	14.97
CaO	.45	5.00	1 20	5.31	6 60	7.91	8 39
Na_2O	3 55	3.91†	3 92	4 26	3 49	2.01	2 38
K_2O	4 83	2.23	3 79	5.22	3 85	4 31	3 06
P_2O_5	.01	.13	03	.73	56	.72	.62

† Includes 0 07 per cent Li_2O.
‡ Includes 0 05 per cent Cl and 0.05 per cent SO_3.
§ Includes 0.02 per cent Li_2O and 0.23 per cent SO_3.

TABLE 1 —AVERAGE COMPOSITIONS.—(*Continued*)

	Dike rocks					
	123	124	125	126	127	128
	Granite-aplite**	Paisanite**	Grorudite	Bostonite	Solvsbergite	Tinguaite
Number of analyses	15	12	5	5	8	15
SiO_2	75 00	73 32	70 91	61.32	62 16	55.02
TiO_2	30	.20	48	89	.31	.36
Al_2O_3	13 14	12 36	11 50	18 43	17 58	20.42
Fe_2O_3	58	1 80	4 58	3.84	3 05	3.06
FeO	40	1.66	1 88	1.60	1.80	1.82
MnO	.07	.08	.39	.01	.18	.22
MgO	30	.14	.11	.46	48	.59
CaO	1 13	.42	39	1 45	1 11	1.67
Na_2O	3 54	4 70	5.43	5.75	7.30	8 63
K_2O	4 80	4.71	4 08	4.94	4.95	5 38
H_2O	71	58	.25	1 31	1 04	2 77
P_2O_5	03	03	..	....	.04	06
Calculated as water free						
SiO_2	75 54	73 76	71 09	62 14	62.82	56 59
TiO_2	30	20	.48	.90	.31	.37
Al_2O_3	13 23	12 44	11 53	18.67	17.77	21.00
Fe_2O_3	.58	1 81	4.59	3.89	3.08	3.15
FeO	40	1.67	1.89	1.62	1.82	1.87
MnO	07	.08	.39	.01	.18	.23
MgO	30	.14	.11	.47	.49	.61
CaO	1 14	42	.39	1.47	1.12	1.72
Na_2O	3.57	4.72	5 44	5.82	7 37	8 87
K_2O	4 84	4.73	4.09	5 01	5 00	5.53
P_2O_5	.03	03	..	. .	04	06

TABLE 1.—AVERAGE COMPOSITIONS.—(*Continued*)

	Dike rocks						
	129	130	131	132	133	134	135
	Spessartite**	Minette	Kersantite	Vogesite	Camptonite	Monchiquite	Alnöite
Number of analyses	10	10	20	4	15	16	6
SiO_2	53 52	49 45	50.79	52 62	40 70	45 17	32 31
TiO_2 .. .	1 24	1 23	1 02	54	3 86	1.90	1 41
Al_2O_3	14 57	14 41	15 26	14 86	16 02	14 78	9 50
Fe_2O_3	3 52	3.39	3 29	3 60	5.43	5 10	5.42
FeO.........	5.29	5.01	5 54	4 18	7.84	5 05	6.34
MnO	38	.13	07	.84	.16	.35	.01
MgO........	6.60	8.26	6.33	8.55	5.43	6 26	17.43
CaO	7 03	6 73	5 73	5.86	9.36	11 06	13.58
Na_2O	3.48	2 54	3 12	3.21	3 23	3 69	1.42
K_2O..	2.28	4.69	2 79	2 83	1 76	2.73	2 70
H_2O.	1 75	3.04†	5.71‡	2.70	5.59§	3 40	7 50‖
P_2O_5	.34	1.12	35	.21	.62	.51	2.38
	Calculated as water free						
SiO_2	54 48	50.99	53 87	54 08	43 10	46.76	34.93
TiO_2 ...	1.26	1.27	1.08	.56	4 09	1 96	1.52
Al_2O_3	14.83	14.86	16 18	15.28	16 97	15 30	10.27
Fe_2O_3	3.58	3.50	3 48	3 70	5 76	5.28	5.86
FeO..	5.39	5.17	5 88 .	4.29	8.30	5.23	6.85
MnO...	.38	.13	.07	.86	.16	.36	.01
MgO	6.72	8.53	6 71	8 79	5 76	6.48	18.84
CaO...	7.16	6.95	6.09	6 02	9 92	11.45	14.68
Na_2O	3.54	2.62	3 31	3 30	3 42	3 82	1 53
K_2O.	2 32	4.84	2 96	2.90	1.86	2 83	2 92
P_2O_5	.34	1 14	37	.22	66	53	2.59

† Includes 0 61 per cent CO_2.
‡ Includes 2 61 per cent CO_2.
§ Includes 2 97 per cent CO_2.
‖ Includes 4.35 per cent CO_2.

INDEX TO TABLE 1

(Figures refer to columns)

Division According to Mode of Occurrence

In a discussion of petrogenesis the separation of the plutonic and volcanic classes of igneous rocks is plainly necessary. Table 1 illustrates the tendency of a plutonic species to be more mafic (lower in silica and alkalies and higher in iron oxides, lime, and magnesia) than the corresponding extrusive species.

Although Brögger's division of the remaining dike class into aschistic and diaschistic rocks is in some instances hard to apply, the underlying idea is helpful. Aschistic dikes are directly apophysal from larger intrusive masses. A diaschistic dike is an offshoot from another mass but represents the effect of more or less thorough differentiation of the feeding magma, whereby the dike comes to differ chemically from the parent.

Igneous-rock Clans

If the 700 named varieties of eruptive rocks were in no sense manifestly related, the problem of origins would be, in very truth, a difficult one. However, field and laboratory observations without number prove the possibility of grouping into relatively few chemical series. For convenience these may be called "clans."

Each clan is composed of families, distinguished less by chemical composition than by mode of field occurrence, by mineralogical composition, or by rock texture. The genetic problem, being most concerned with the explanation of chemical diversity, is simplified by recognition of the fact that the clans represent so many chemical groups, each of which contains syngenetic families. For example, the problem is essentially the same for magmas of the syenite family, the syenite porphyry family, and at least some members of the trachyte family. The chemical similarity of gabbro, gabbro porphyrite, diabase, diabase porphyrite, basalt, melaphyre, and other species suggests their common origin. On the other hand, the diorite family, like some others, includes species of different lines of descent; thus the diorite clan is a somewhat artificial division, yet recognized for convenience in the following discussion.

The more important groups are the granite clan, the granodiorite clan, the diorite clan, the gabbro clan, the syenite clan, the ultramafic clans, and the "feldspathoidal" clans. To them, Chapters XVI to XXII inclusive apply specifically the general theory of rock origins outlined in the seven chapters immediately preceding.

CHAPTER III

DISTRIBUTION AND RELATIVE QUANTITIES OF IGNEOUS-ROCK SPECIES

General Distribution

Probably all of the clans are represented in each of the seven continents. While most clans are represented in the islands of the open ocean, granite, granodiorite, and other quartz-bearing plutonics seem to be wanting in the deep-sea islands, except where these may reasonably be assumed to rest upon sunken blocks of rock like that dominating at the surface of a continent. However, this relation is not manifest in the case of small bodies of rhyolitic obsidian and quartz trachyte erupted through the prevailing basalts of Easter Island and Tutuila Island, respectively.[1]

The attempts to establish a law localizing the "alkaline suite" of rocks in the Atlantic region and the "subalkaline suite" in the Pacific region have failed. Nor has better success attended the effort to connect the distribution of the "alkaline" rocks with one type of crustal deformation (normal faulting on the large scale) which is supposed specially to characterize the Atlantic basin. In the opinion of the author "Atlantic branch" and "Pacific branch," like "Arctic

[1] For long distances around the Easter Island cone the depth of the water is about 3500 meters or 1500 to 2000 meters less than that characterizing the vast northwestern part of the Pacific basin. This relative shallowness permits the hypothesis that there is a thin Sialic layer under the island, though situated more than 3000 kilometers from the nearest continent, South America. Yet we cannot exclude the possibility that the obsidian, with 72 per cent silica, is an acid differentiate of uncontaminated basalt. It is, indeed, a remarkable fact that T. F. W. Barth (Amer. Jour. Science, vol. 21, 1931, p. 501) has identified quartz in the groundmass of a Kilauean picrite-basalt, as if olivine had separated in excess.

The quartz trachyte of Tutuila Island, Samoa, presents a somewhat similar problem (see R. A. Daly, Pub. 340, Carnegie Inst. of Washington, 1924, p. 121). So it is also with the granite bombs in the lavas of the Kermadec Islands (R. Speight, Trans. New Zealand Inst., vol. 42, 1909, p. 241), and with the rhyolitic type found in the Marquesas Islands (Barth, op. cit., p. 525).

A. Lacroix (Mém. Acad. Sci. Paris, vol. 59, 1927, p. 63) doubts that either pure melting or assimilation was concerned in the generation of the Easter Island rhyolite. The alternative explanation (differentiation from basaltic liquid) suffers from the fact of the extreme rarity of free quartz and of rhyolitic types in deep-sea volcanoes, even where the differentiation of the ruling basalt has been well advanced.

branch" and "Mediterranean branch," are not happy designations for the petrographic facies which they are taken to represent. The names have little justification in geography. If used at all, they must be recognized as purely symbolic; hence the first thing a student of petrography has to learn about them is that these names do not mean what they appear to mean. Nor have any generally acceptable definitions of the five expressions been formulated.[1]

Petrographical provinces exist, but one province may be more or less closely duplicated in another continent or ocean basin. The rock types found in the Monteregian Hills, Quebec, correspond in essential details with those of the Adirondacks, of Mount Ascutney, Vermont, or of the Oslo region, Norway. The special combination of anorthositic and syenitic species in the Adirondacks recalls that of western Norway. The rock associations of the Bohemian "alkaline" province are more or less fully repeated along the Great Rift of Africa, in central France, in Tahiti, in the Canary Islands, and in the Azores. These and other examples go to show that the petrogenetic mechanism has worked after much the same fashion beneath each of the continents and, with exceptions to be described later, beneath each of the deep oceans. A degree of sameness in the midst of variety is a principal result of the earth's igneous activity.

Need for Quantitative Study

Largely because the rarer species are the more "interesting," petrographers have continued to emphasize the diversity of igneous rocks. Like every other science, theirs has had to be analytic before it could be healthfully synthetic. But there is no little danger of a false perspective if, in the search for specific distinctions, a considerable effort is not made to estimate the actual value of those distinctions. Above all, petrography needs to be closely linked with areal and structural geology, so that the problem of rock origins may be phrased in terms of the relative volumes of the different species.

The data for such a quantitative study fall far short of being complete enough for the ultimate aim of petrology. Yet the documents already published suffice for a few important conclusions from a synthetic study. Some of these will doubtless stand fast when the

[1] A useful collation of the facts of distribution of igneous species is found in F. von Wolff, Der Vulkanismus, Stuttgart, 1914–1929. Compare the chemical studies of petrographical provinces by C. R. Burri (Schweiz. Min. u. Petr. Mitt., vol. 6, 1926, p. 115, and vol. 7, 1927, p. 254). F. Loewinson-Lessing (Bull. soc. géol. France, vol. 23, 1923, p. 144) shows that the highly typical "Atlantic" miaskites of the Ural Mountains occur in an orogenic zone of the "Pacific" type. Many similar cases will be noted in the sequel.

whole earth becomes as fully known as the explored parts of Europe and North America.

The statistical work might well be done by a representative committee of the International Geological Congress. Until that body or a similar group of properly equipped specialists chooses the great task, it would seem futile for anyone to try to state the genetic problem of the igneous rocks with the completeness and clarity now possible. Only a few quantitative tests can be applied to the geological maps by the individual petrologist without his performing an unreasonable amount of labor. Among the significant questions are the following: (1) What are the relative areas of the earth's surface covered by the different species of igneous rocks? (2) How do the respective total areas of the alkaline and subalkaline bodies compare? (3) What is the largest known body of rock representing each of the clans?

Relative Quantities in the United States

For the petrographer as for the geographer, North America is in many respects the "typical continent." A first approximation to an estimate of the relative areas covered by igneous species throughout the world would be possible if complete measurements were now at hand for this one continent. Even the scanty record of the present day points to certain principal facts of distribution.

The igneous rocks of North America are almost entirely confined to three regions, the Pacific Cordilleran system, the so-called "Appalachian" belt, and the Pre-Cambrian shield of Canada and its outliers. In the United States the geology of the Cordilleran and Appalachian regions has been sampled during the preparation of the folios issued by the Federal geological survey. The number and distribution of the folio areas show that the sampling so far accomplished roughly indicates average quantitative relations among the exposed igneous rocks of the two regions. On the whole, too, the standard of detail and accuracy set for the folios is fairly uniform; the field conclusions have been checked with more or less thoroughness by microscopic and chemical examination of the rocks.

The total area of the United States proper is 3,030,000 square miles. Of this, about 159,000 square miles are covered by the folios published up to Jan. 1, 1912. The Cordilleran area is about 800,000 square miles and its fifty-nine folios in which igneous formations are mapped cover a total area of 60,990 square miles. The Appalachian area is somewhat less than 200,000 square miles; within it the sixteen folios showing igneous formations cover a total area of 13,221 square miles. The total areas covered by igneous types in these two groups of quadrangles are shown in Table 2.

The measurements for each folio were not made with extreme nicety, expenditure of time and work useless for present purposes thus being avoided. However, the orders of magnitude are believed to be correctly stated. The areas of rock types showing small extension

TABLE 2.—RELATIVE AREAS

Plutonic rocks	Pacific Cordillera, square miles	Appalachian belt, square miles	Total, square miles
Pre-Cambrian granite	2,089 0	1,151 0	3,240.0
Paleozoic and later granite	402 0	194 0	596.0
Total granite	(2,491 0)	(1,345 0)	(3,836 0)
Granodiorite	2,040 0	.....	2,040.0
Quartz monzonite	11 0	. .	11 0
Quartz diorite	45 3	...	45.3
Diorite	103 5	10 0	113.5
Gabbrodiorite	98 5	.....	98.5
Gabbro	226 4	47.5	273.9
Anorthosite	52.0	......	52.0
Syenite	24.4	......	24.4
Monzonite	17.5	....	17.5
Nephelite syenite	3 5	.3	3.8
Shonkinite	8 7	......	8.7
Fergusite	<1 0	. . .	<1 0
Missourite	1	. .	.1
Theralite	6 3		6 3
Peridotite	73 3	.....	73.3
Pyroxenite	2 2	. .	2 2
Totals	5,204 7	1,402.8	6,607.5

"Hypabyssal rocks" (intrusive)	Pacific Cordillera, square miles	Appalachian belt, square miles	Total, square miles
Granite porphyry	17 9	2 0	19.9
Quartz porphyry and rhyolite	26.5	1 0	27 5
Dacite porphyrite	7.8	...	7.8
Quartz-hornblende porphyrite	2 0	.....	2.0
Quartz monzonite porphyry	4.6	......	4.6
Diorite porphyrite	20.1	1.6	21.7
Hornblende porphyrite	1 0	......	1.0
Quartz diabase	3.0	......	3.0
Diabase	150.0	118 0	268.0
Syenite porphyry	38.4	2.5	40.9
Monzonite porphyry	9.4	....	9.4
Nephelite syenite porphyry	< .1	....	< .1
Phonolite	2.7	....	2.7
Pseudoleucite porphyry	.5	......	.5
Totals	284.0	125 1	409.1

TABLE 2.—RELATIVE AREAS—(*Continued*)

Extrusive rocks	Pacific Cordillera, square miles	Appalachian belt, square miles	Total, square miles
Rhyolite	2,145.7	1.0	2,146 7
Dacite	82.1	....	82.1
Mica andesite	3 0	...	3.0
Hornblende andesite	21 6	....	21.6
Pyroxene andesite (chiefly)	3,966 0	....	3,966.0
Augite porphyrite	255 0	.....	255.0
Basalt	3,079 0	130 0	3,209.0
Trachyte	6 5	...	6.5
Latite	4.6	...	4.6
Phonolite	5.5	....	5.5
Trachydolerite	.3	....	.3
Teschenite	.2	..	.2
Nephelite-basalt (Texas)	1.2	....	1.2
Nephelite-melilite basalt (Texas)	2.8	....	2.8
Limburgite	2.5	....	2 5
Quartz basalt	8 0	....	8.0
Totals	9,584.0	131.0	9,715 0
Total igneous-rock area mapped	15,072 7	1,658 9	16,731.6

were measured with special care. Composite terranes, respectively including several igneous species but mapped under one color, were neglected. Some terranes of greatly altered rocks were similarly excluded from consideration.

In estimating the relative volumes corresponding to the areas listed, we note that many of the "plutonic" bodies are really sheets, laccoliths, or irregular injections and hence do not extend to great depths. This is true, for example, of all the theralite mapped, of some diorites, and of many shonkinitic, monzonitic, and syenitic masses. It is not certain that any of the gabbros keeps its length and breadth to a depth of more than a few thousands of meters. On the other hand, since most of the granite, granodiorite, and quartz diorite bodies have depths to be reasonably estimated in kilometers, the horizontal sections of these bodies are likely to be at least as extensive as at the outcrop. Hence several of the plutonic types with small total areas are doubtless still more subordinate with respect to total volume.

Again, observation shows small total area of an effusive type to be generally accompanied by small average thickness.

Thus, whether we compare the plutonics *inter se* or the effusive rocks *inter se*, we see that the volumes of the less extensive eruptives in the folio quadrangles are likely to have even lower ratios to the volumes of the other eruptives than those between their respective areas at the outcrop.

Relative Abundance of the So-called "Alkaline" Rocks

The "alkaline provinces" of the Cordilleran belt include some of the most extensive known anywhere and are also rich in types. In this part of the world the shonkinites, missourites, fergusites, theralites, and latites were first named and described. Perhaps no other region of equal size carries more numerous distinct bodies of monzonite than does the United States portion of the Cordillera. The relative abundance of the alkaline, quartz-free to quartz-poor rocks of the Cordillera as a whole is probably no greater than that illustrated in the Geological Survey folios so far published. Hence the following conclusions, directly derivable from Table 2, are significant.

The combined area of all the syenites, nephelite syenites, monzonites, shonkinites, missourites, fergusites, and theralites of the Cordilleran quadrangles is about 61 square miles out of a total of the 5205 square miles covered by all the plutonic types of these quadrangles. The combined area of the syenite porphyries, monzonite porphyries, nephelite-syenite porphyries, pseudoleucite porphyries, and intrusive phonolite is 51 square miles out of a total of 284 square miles of hypabyssal rocks. The combined area of the extrusive trachytes, latites, trachydolerites, phonolites, teschenites, nephelite basalts, and limburgites is about 23 square miles out of a total of 9584 square miles of extrusives. The combined area of all the mapped alkaline rocks (including syenites and trachytes) in the Cordilleran quadrangles is about 135 square miles out of a grand total of about 15,000 square miles of igneous rocks.

As more detailed work is done, the totals for the alkaline rocks will doubtless be enlarged, but it seems certain that all totals for this group of rocks must, throughout the Cordilleran belt, be found extremely small when compared with the totals for the subalkaline types.

The sixteen Appalachian folios, showing 1659 square miles of igneous rocks, have only 0.3 square mile of nephelite syenite and 2.5 square miles of syenite porphyry to represent the whole alkaline group, including syenites and trachytes.

The total area of the alkaline rocks covered by the folios of both belts of mountains is about 140 square miles out of 16,700 square miles of igneous formations. Considering the relatively small thicknesses of most of the alkaline bodies (sheets, laccoliths, lava flows, beds of pyroclastics), the total volume of alkaline rock exposed in these quadrangles may be taken as far less than one-half of 1 per cent of the total volume of subalkaline rock.

The ratio for North America as a whole is also small. Including the large syenite, nephelite syenite, and malignite masses mapped in

New York State (150 square miles), New Hampshire (21 square miles), Ontario (100 square miles), and British Columbia (*ca.* 200 square miles), the total area of alkaline rocks actually mapped in this continent, outside the United States Geological Survey folios, is slightly over 500 square miles. In all, then, about 700 square miles of alkaline rocks (including syenite) have been mapped in North America.

In the Cordilleran belt about 170,000 square miles of post-Cambrian plutonics are indicated on the map of North America published by the United States Geological Survey. These rocks are chiefly granodiorites, granites, and quartz diorites. In the same belt more than 400,000 square miles of post-Cambrian volcanics are shown on the map; most of them are basalts and the rest chiefly andesites.

The Appalachian belt of the map has about 30,000 square miles of post-Cambrian extrusives, almost entirely subalkaline and chiefly granitic.

The grand totals for the post-Cambrian intrusives and extrusives of the continent as a whole are, respectively, about 200,000 and 400,000 square miles. The Pre-Cambrian granites and orthogneisses cover at least 1,000,000 square miles.

We may conclude that the known quartz-free alkaline rocks of North America have a combined area less than 0.05 per cent of the total known area of the igneous rocks. The ratio of volumes is then probably much less than 0.1 per cent.

European maps seem to give ratios of the same orders of magnitude. Their closer determination is a highly desirable undertaking by the various geological commissions of Europe. The alkaline bodies are numerous but, with few exceptions, small. Though phonolite was first named in Germany, the eye is much strained to find the tiny spots of color for phonolite on Lepsius's map of the Reich. The Tertiary nephelite basalts, melilite basalts, and limburgites are exceptionally well developed in Germany, but, taken together, they are probably far inferior in volume to ordinary plagioclase basalt and *a fortiori* to the pre-Tertiary eruptives of the Reich. Though trachyte was first named in France, neither this species nor phonolite could be profitably indicated with special color on the beautiful Survey wall map of France. The large-scale maps show the total volume of the French alkaline bodies to be much less than 1 per cent of the combined subalkaline masses of that country. A similar statement applies to the British Islands, Switzerland, Finland, and Spain. The ratio is probably somewhat higher in the case of Scandinavia, Italy, and Portugal.

For Europe as a whole the ratio is likely to be smaller than 1:100. For Asia, Africa, Australia, and Antarctica the data are manifestly

poorer, but there is nothing yet to indicate that the ratio is greater than 1:1000.

However imperfect may be the result of this extrapolation from ascertained facts, a definite conclusion is already clear: the alkaline clans, though including more than half of the named igneous species, are only incidental products of a planet whose eruptions have been overwhelmingly of the subalkaline kind. This fact cannot fail to bulk large in any theory of petrogenesis.

Relative Abundance of the Subalkaline Clans

Table 2 shows significant quantitative contrasts between the group of diorites (excluding quartz diorite), gabbros (including gabbro-diorite and anorthosite), and peridotites on the one hand, and both granite and granodiorite on the other.

The first three plutonics named constitute many distinct bodies, but their total areas in the folio quadrangles are respectively less than 4, 10, and 2 per cent of the total area of granite, and respectively less than 6, 19, and 4 per cent of the total area of granodiorite. Ratios of the same order characterize the whole of North America.

Equally evident is the dominance of the *extrusive* members of the basic clans over the extrusive members of the granite and granodiorite clans, with regard to both total areas and average thicknesses.

A study of geological literature in general seems to warrant the following generalizations for the world's outcrops:

Ratio of total areas, granite to diorite, greater than 20:1.
Ratio of total volumes, rhyolite to andesite, less than 1:10.
Ratio of total areas, granite to gabbro, greater than 20:1.
Ratio of total volumes, rhyolite to basalt, less than 1:50.

Thus the basic subalkaline clans predominate among the extrusives; the acid subalkaline clans predominate among the intrusives.[1]

Species Known Only in Small Volumes

Of the ten families of plutonic rocks discussed in Rosenbusch's handbook, four families are but feebly represented among the world's terranes. The total known area of the bodies corresponding to each of these families is probably less than 150 square kilometers. Specifically, the upper limits, in square kilometers, may be stated as follows:

Essexites	150
Shonkinites (50) and Theralites (50), largely sheets and laccoliths	100
Missourites (3) and Fergusites (3)	6
Ijolites (15) and Bekinkinites (3)	18

[1] *Cf.* J. J. Sederholm, Bull. Comm. Géol. Finlande, No. 22, 1907, p. 108.

The andesites and porphyrites may have a total area approximating one-fifth of that of basalt. Next in order comes the rhyolitic group. The remaining eleven families all have small total volumes; none is known to have a total of as much as 1 per cent of the basaltic masses already demonstrated. These particularly subordinate extrusives are

Trachytes and quartz-free porphyries.
Phonolites.
Trachyandesites.
Dacites and quartz porphyrites.
Picrites and picrite porphyrites.
Trachydolerites.
Tephrites and basanites.
Leucite rocks.
Nephelite rocks.
Melilite rocks
Limburgites and augitites.
Lamprophyric effusive rocks.

Some Conclusions

As petrographic literature issues from the press year by year, it shows that new discoveries do not essentially alter the relative position of the rock families, considered quantitatively. This is true notwithstanding the tendency of petrographers to emphasize the rarer species in their publications. The more objective product of the government surveys is a useful corrective to the psychological bias. Based particularly upon such data, certain generalizations appear sound, even though built upon limited exact knowledge concerning the earth.

1. The visible quartz-poor and quartz-free alkaline rocks of the world, including the syenite (with monzonite) clans, have total volume probably less than 1 per cent of that of the visible subalkalines.

2. Among the visible intrusive rocks, the granites and granodiorites together have more than twenty times the total area of all the other intrusives combined.

3. Among the extrusives, basalt probably has at least five times the total volume of all the other extrusives combined; basalt and pyroxene andesite together have at least fifty times the volume of all other extrusives combined.

4. The granite and granodiorite clans, though dominant among the intrusives, are among the subordinate clans represented in the extrusives.

5. The diorite clan is decidedly subordinate among the intrusives but rates next to the gabbro clan among the extrusives.

6. The gabbro clan is likewise subordinate among the intrusives but predominates among the extrusives.

7. The igneous rocks of the globe belong chiefly to two types: granite and basalt. The truth was long ago recognized by Durocher, von Cotta, and Bunsen, and later by Michel Lévy, Loewinson-Lessing, Harker, Joly, Bowen, and others. Richardson and Sneesby have again proved it, by a method quite different from that just outlined.[1] To declare the meaning of the fact, that one of these dominant types is intrusive and the other extrusive, is to go a long way toward outlining petrogenesis in general.

Maximum Size of Individual Bodies

To visualize the problem of origins ideally, it would be necessary to know the sizes of the bodies corresponding, respectively, to the intrusive and extrusive members of each clan. Manifestly this ideal cannot be reached. However, it is worth while to glance at estimates of the outcrop areas of the largest mapped representatives of the intrusive species (Table 3).

Table 3

Rock type	Location	Area, km²
Pre-Cambrian granite	Post-Bottnian "central" granite of Finland	23,000
Granodiorite	Sierra Nevada, California	50,000
Quartz monzonite	Bitterroot Range, Idaho	8,000
Quartz diorite	Southern Alaska	12,000
Diorite	Little Belt Mountains, Montana	65
Gabbro (lopolith)	Duluth district, Minnesota	6,100
Anorthosite (laccolith?)	Saguenay district, Quebec	15,000
Subalkaline syenite	Ceara, Brazil	1,200
Pulaskite	Coryell batholith, British Columbia	250
Nordmarkite	Nordmarken, Norway	2,000
Nephelite syenite	Kola Peninsula	1,800
Laurvikite	Laurvik, Norway	600
Malignite	Pooh Bah Lake, Ontario	38
Monzonite	Telluride Quadrangle, Colorado	20
Essexite	Shefford Mountain, Quebec	4
Shonkinite (laccolith)	Square Butte, Montana	10
Missourite (stock)	Shonkin, Montana	<1.8
Fergusite (stock)	Arnoux, Montana	<2 5
Theralite (laccolith)	Northern Crazy Mountains, Montana	10
Ijolite	Kuusamo parish, Finland	<2
Bekinkinite	Bekinkina Mountains, Madagascar	<2

[1] W. A. Richardson and G. Sneesby, Miner. Mag., vol. 19, 1922, p. 313.

CHAPTER IV

ERUPTIVE TYPES AND GEOLOGICAL TIME

Like the space relations of igneous rocks, the time relations can here be only briefly sketched. Some of the essential facts are tabulated in Appendix B of "Igneous Rocks and Their Origin." The first part of the table exemplifies Pre-Cambrian sequences; the second part, sequences running from the Pre-Cambrian onwards; the third part, sequences restricted to post-Cambrian time. Some of the series refer to igneous development in whole countries, like the British Isles or Germany; others refer to small areas, such as the Eolian Islands or the single island of Vulcano. Each type of succession, considered in relation to the detailed facts of the original monographs, is significant for petrological theory.

Within an extensive igneous field the eruptions generally, if not always, form groups that are separated by long intervals of time. Any of the intervals may be one or more of the standard geological periods, like the Triassic or Eocene, or may represent merely times of prolonged erosion. These breaks in succession separate the different *petrogenetic cycles* for the various regions, though, on account of the conservative recording of the time gaps in the 1914 table, the total number of cycles there indicated is a minimum.

RECURRENCE OF TYPES BELONGING TO THE GABBRO CLAN

The chemical type most commonly appearing in the cycles is the basaltic. Gabbro, diabase, basalt, or their chemical equivalent appears in 56 of the 62 series listed, and in 96 of the 116 different cycles. This kind of magma initiates the sequence for each of 68 cycles, from the time of the hoary Keewatin lavas to the cycle of the living Kilauea.

Besides being the most frequent, basaltic extrusions have also had the greatest average volume during any of the longer divisions of geological time. The fields of plateau basalt illustrate this fact.

On the other hand, plutonic members of the gabbro clan are, as a rule, subordinate to granite of the same cycle. The relation is here similar to that we have already found for the present distribution of eruptive rocks regardless of age.

Recurrence of Other Clans

Except two clans, all are represented by both Pre-Cambrian and Cenozoic eruptions. The missourite-fergusite and theralite clans have not yet been shown to appear among the Pre-Cambrian rocks, but they are of almost negligible quantitative importance. Thus in the first of the greater divisions of geological time, as in the last, the eruptives were essentially of the same quality. The majority of the clans are registered also among the Paleozoic and Mesozoic magmas. Any general theory must account for this eruption of each of the chief chemical types at intervals from at least the later Pre-Cambrian to the present time.

Time Relations of the Granite and Granodiorite Clans

Yet for some of the clans, Nature has varied the accent in the geological record. More than nine-tenths of the area of the world's granite (including orthogneisses and excluding the granodiorites) belongs to the Pre-Cambrian terranes. Allowing for the Pre-Cambrian granites beneath the younger sediments, this fraction is likely to be nearer 99:100.

Notwithstanding prolonged erosion, the Pre-Cambrian shields are also rich in the effusive members of the granite clan—rhyolites, quartz porphyries, leptites.

Although of late years granodioritic rocks have been identified in the Archean terranes, the known masses belonging to the granodiorite clan are largely of post-Cambrian dates.

Time Relations of the "Alkaline" Clans

Jensen has argued that the quartz-poor, alkali-rich rocks are almost entirely of Tertiary eruption.[1] Multiplying discoveries of pre-Tertiary nephelite syenites, ijolites, malignites, lujavrites, etc., show that this generalization must be seriously qualified. It is only natural that the pre-Tertiary alkaline masses, because of their characteristically small volumes, should have been destroyed or much diminished by erosion or else buried under sediments of many different ages. Yet the Cenozoic era may have been a time of special development of alkaline eruptives, both as regards breadth of distribution and total volume.

Time Relations of Anorthosite

This is the only plutonic species whose voluminous eruptions seem to be confined to one part of geological time. All of its larger visible

[1] H. I. Jensen, Proc. Linn. Soc. New South Wales, vol. 33, 1908, p. 491.

masses seem to be of Pre-Cambrian, probably late Pre-Cambrian, dates. Even the Norwegian anorthosites, previously referred by C. F. Kolderup to a late Silurian or post-Silurian epoch, are now regarded by N. H. Kolderup and T. Barth as Pre-Cambrian.[1] Since this type is conspicuous in the field, the special time relation stated cannot be regarded as a wrong induction due to the accidents of geological discovery.

Dike Rocks in Geological Time

The diaschistic dikes deserve a special note. Their dating is generally more difficult than that of the larger intrusions. Those so far reported from the Pre-Cambrian are almost wholly aplites and pegmatites. Very rare or quite wanting in the Pre-Cambrian are bostonite, cuselite, fourchite, gauteite, kersantite, minette, odinite, ouachitite, sölvsbergite, spessartite, and vogesite. The many expert petrographers who have ranged widely over Fennoscandia, the Canadian shield, the Adirondacks, the Pre-Cambrian of the North American Cordillera, the African shield, and the peninsula of Hindustan have certainly not been oblivious to the attraction of the diaschistic dikes. In conclusion, it appears safe to attribute the development of magmas chiefly to post-Cambrian time.

Modes of Eruption and Geological Time

Table 21, page 119, shows that intrusions of the batholithic kind date from the Pre-Cambrian, the close of the Ordovician (?), the Devonian, the Carboniferous, the Jurassic, the early Tertiary, the Miocene, and probably the Pliocene. Basaltic fissure eruptions were incidents of many periods (see Table 33, page 264). The gabbro and anorthosite bodies of the Pre-Cambrian are probably laccolithic or lopolithic in origin; the conditions seem to have been then specially favorable for the development of these big, monolithic basic masses. Still earlier lit-par-lit injection of granitic melts was long the dominant mode of eruption; many of the so-called "batholiths" of the Archean are really thick sills or injected lenses. The world-wide character of this Archean process has meaning in connection with the difficult subject of the earth's original crusting and will be considered again in the later, theoretical chapters.

[1] C. F. Kolderup, Bergens Museum Aarbog, No. 5, 1896, and No. 12, 1903. N. H. Kolderup, *ibid.*, 1928. Tom F. W. Barth, Neues Jahrb. f. Mineralogie, etc., B.B. 58 (A), 1928, p. 420.

Summary

Incomplete as induction must be at the present time, some general conclusions appear to be justified.

1. Qualitatively, the intermittent eruption of magmas has tended in a general way to follow uniformitarian lines. With respect to chemical diversity and modes of eruption the visible Pre-Cambrian, Paleozoic, and Mesozoic bodies much resemble Tertiary bodies.

2. Yet that rule is subject to the following exceptions: (*a*) the extraordinary eruptivity of the Pre-Cambrian; (*b*) the excessive emplacement of granite by pure injection during the early Pre-Cambrian; (*c*) the restriction of all of the larger masses of anorthosite to (apparently late) Pre-Cambrian dates of eruption; (*d*) the special development of the quartz-poor, alkali-rich rocks and of the granodiorite clan in post-Cambrian, particularly post-Paleozoic, time; (*e*) the stronger diversification of types among the diaschistic dikes after Pre-Cambrian time.

The explanations of these certain or highly probable facts are so many items in the petrogenetic problem.

CHAPTER V

SOME PHYSICAL PROPERTIES OF ROCKS

For convenience of reference, data regarding the physics of rocks are recorded in the present chapter. The statement is far from being exhaustive but includes specially significant results of experiments on rocks, minerals, and glasses.

Density.—A fundamental fact about an igneous rock is its average specific gravity. Unfortunately, most authors have neglected to state, with each new chemical analysis, the density of the analyzed specimen. This is the case with many hundreds of magnificent analyses published by officers of the United States Geological Survey. It would be a valuable contribution of petrology if the densities of all original analyzed specimens in the collections of that Survey and of similar institutions were determined and the results published. Among others Becke emphasized the importance of such determinations for petrology.[1]

Relations of rock densities are crucial for many questions relating to magmatic equilibria and differentiation, the emplacement of magmatic bodies, metamorphism, mountain building, the nature of the earth's interior, the facts of seismology, and the theory of isostasy.

From the latest edition of Washington's "Chemical Analyses of Igneous Rocks."[2] most of the figures for specific gravities of some holocrystalline species, at room temperature, have been extracted. To these have been added a few other determinations. Simple averages have been computed and entered in Table 4, which shows also the range of specific gravity for each species.

The International Critical Tables give for range of bulk density:

Gneiss	2.7–2.95
Schist	2.7–2.95
Marble	2.7–2.85
Limestone	2.3–2.7
Slate	2.7–2.8
Sandstone	2 2–2.6

[1] F. Becke, Sitzungsber. k. Akad. Wiss., math.-naturw. Kl., vol. 120, 1911, p. 265.

[2] Prof. Paper 99, U.S. Geol. Survey, 1917.

TABLE 4.—SPECIFIC GRAVITIES

Rock type (as named by authors)	Number of determinations in average	Range of specific gravities	Average specific gravity
Granite	155	2 516 -2.809	2 667
Granodiorite	11	2 668 -2.785	2.716
Quartz monzonite	9	2 640 -2 837	2.715
Tonalite	6	2 679 -2.837	2.751
Syenite	20	2.630 -2.899	2.729
Nordmarkite	3	2 659 -2.683	2.672
Pulaskite	4	2 581 -2 772	2.672
Akerite	1	....	2.612
Umptekite	2	2 672 -2 732	2 702
Monzonite	10	2 700 -2 847	2 786
Nephelite syenite	8	2.521 -2 666	2 606
Foyaite	3	2 596 -2 751	2.649
Naujaite	2	2.530 -2.545	2 537
Lujavrite	6	2.67 -2 85	2.775
Shonkinite	2	2.94 -2 95	2 945
Ijolite	3	2.892 -3 084	2.990
Diorite	17	2.721 -2.980	2 871
Gabbro, including olivine gabbro	27	2.850 -3.120	2 976
Dolerite	31	2.664 -3.124	2 922
Diabase, fresh, excluding quartz diabase	40	2.804 -3.152	2 980
Essexite	10	2 686 -2.919	2.838
Peridotite, fresh	3	3.152 -3.276	3 234
Dunite, fresh (Balsam Gap, North Carolina)	1	....	3.289
Wehrlite	1	....	3.370
Harzburgite	1	....	3.075
Websterite	3	3.301 -3.340	3.315
Lherzolite	1	....	3 330
Average of last five types, as named	9	....	3.270
Pyroxenite	8	3.10 -3.318	3.231
Anorthosite	10	2.640 -2.920	2.754
Eclogite[1]	14	3 205 -3.689	3 376
Eclogite of Norway[2]	4	3.415 -3.61	3 526
Plateau basalt (Oregonian)[1]	3	2 805*-3 002	2.897
Plateau basalt (Deccan)[1]	4	2 932 -3.025	2.982
Plateau basalt (Hebridean)[1]	5	2.818*-2.978	2.912
Island basalt (Atlantic)[1]	6	2 870 -3.070	2.954
Island basalt (Pacific and Indian oceans)[1]	6	2.661*-2.967	2 827

[1] From J. H. J. Poole, Phil. Mag., vol. 3, 1927, p. 1246.
[2] From P. Eskola, Videns.-Skrifter, Oslo, Kl. I, 1921, No. 8.
* Glass present?

The computed figure for the third place of decimals is given in Table 4, but in most cases can hardly be called significant. The average specific gravity for 58 granites[1] is 2.660 and that now stated for 155 granites is 2.667. For the majority of types many more determinations are needed before even the first place of decimals can be stated with confidence. To better the situation by reporting the much-needed data for the individual rock is the duty of petrographer, chemist, and physical geologist.[2] The difficulty of making perfectly accurate determinations and the actual variability of each mass of rock should not inhibit such measurements; for, as the number of these grows, errors tend to cancel out.

Experiments by Bischof, Delesse, Cossa, Barus, Joly, Douglas, Tilley, and others have shown the glassy phase of rock to be less dense than the corresponding holocrystalline phase at the same temperature.[3] Of special value are the actual measurements by Day, Sosman, and Hostetter of the Geophysical Laboratory at Washington. Their results are here summarized for fresh Palisade diabase:

	At 20°C.	At 1200°C.
Specific gravity of crystalline rock	2 975	2 89
Specific volume of crystalline rock	336	346
Specific gravity of equivalent glass	2 761	2 603
Specific volume of equivalent glass	362	.384

MEAN COEFFICIENT OF EXPANSION BETWEEN 20° AND 1200°

For crystalline rock	25×10^{-6}
For equivalent glass	50×10^{-6}
For equivalent glass (20° to 900°)	42×10^{-6}

PERCENTAGE DECREASE OF SPECIFIC GRAVITY

Crystalline rock at 20° to glass at 20°	7.19
Crystalline rock at 20° to glass at 1200°	12.5
Crystalline rock at 1200° to glass at 1200°	9.9
Glass at 20° to glass at 1200°	5 7

The results of Douglas (room temperature in all cases) are shown in the table at the top of page 49.

The gabbro and dolerites are all comparable with the Palisade diabase, for which the percentage decrease of specific gravity at room temperature was found by Day, Sosman, and Hostetter to be consider-

[1] Igneous Rocks and Their Origin, p. 39.

[2] *Cf.* H. S. Washington, Bull. Geol. Soc. America, vol. 33, 1922, p. 401.

[3] G. Bischof, L. and J. Jahrb. f. Mineralogie, etc., 1841, p. 565; *cf. ibid.*, 1843, p. 1. A. Delesse, Bull. soc. géol. France, vol. 4, 1847, p. 1380. A. Cossa, quoted in Zirkel's Lehrbuch der Petrographie, vol. 1, Leipzig, 1893, p. 681. C. Barus, Bull. 103, U.S. Geol. Survey, 1893. J. Joly, Trans. Roy. Soc. Dublin, vol. 6, 1897–1898, p. 283.

	Specific gravity of crystalline rock	Specific gravity of glass	Percentage decrease of specific gravity
Granite, Shap Fells	2 656	2 446	7.90
Granite, Peterhead	2 630	2 376	9.66
Syenite, Plauen'scher Grund	2.724	2.560	6 02
Tonalite, New Zealand	2 765	2.575	6 87
Diorite, Guernsey	2.833	2.680	5.40
Diorite, Markfield	2.880	2.710	5.90
Gabbro, Carrock Fell	2 940	2.791	5.07
Olivine dolerite, Clee Hills	2 889	2.775	3.95
Dolerite, Rowley Rag	2.800	2.640	5 71
Dolerite, Whin Sill	2 925	2.800	4 27

ably greater. This difference of results remains unexplained. With proper adjustment Barus's older figures agree rather closely with those obtained at the Geophysical Laboratory.[1]

Valuable contributions on the densities of natural rock glasses have been made by Tilley, George, and Mickey.[2] From Tilley's tables the average specific gravity (at 4° C., corresponding to values at room temperature, within limits of experimental error) of rhyolite obsidian, trachyte obsidian, and basalt glass have been computed. In the last case, however, the value for the abnormal material from the island of Eigg was omitted, and the values accurately measured by Barus and by Day, Sosman, and Hostetter for (artificial) diabase glass were added. The computed averages, distinguished by the letter *T*, are given in Table 5, which also contains corresponding values, marked *G*, for pitchstone and dacite, andesite, and leucite-tephrite glasses,

TABLE 5.—SPECIFIC GRAVITIES OF ROCK GLASSES

Rock glasses	Number of determinations	Average specific gravity	Range of specific gravity
Rhyolite obsidian (*T*)	15	2.370	2.330–2 413
Rhyolite obsidian, Caucasus (*M*)	6	2.352	2.347–2 363
Trachyte obsidian (*T*)	3	2.450	2 435–2 467
Basalt glass (*T*)	11	2 772	2.704–2 851
Pitchstone (*G*)	4	2 338	2.321–2.37
Dacite glass (*G*)	..	2.505	2.45 –2.55
Andesite glass (*G*)	3	2 474	2.40 –2.573
Leucite tephrite glass (*G*)	2	2.55	2.52 –2 58

[1] A. L. Day, R. B. Sosman, and J. C. Hostetter, Amer. Jour. Science, vol. 37, 1914, p. 1; J. A. Douglas, Quart. Jour. Geol. Soc. London, vol. 63, 1907, p. 145.

[2] C. E. Tilley, Miner. Mag., vol. 19, 1922, p. 275. W. O. George, Jour. Geol., vol. 32, 1924, p. 353. I. J. Mickey, Centralbl. f. Mineralogie, etc. (A), 1930, p. 416.

TABLE 6.—SPECIFIC GRAVITIES OF CRYSTALS AND CORRESPONDING GLASSES
(Room temperature and pressure)

	Specific gravity, crystal	Specific gravity, glass	Decrease on vitrification, per cent	Authority
Anorthite (Mte. Somma)	2 750	2 665	3 1	Douglas
Anorthite	2 765	2 700	2.35	Geophysical Laboratory
Ab_1An_5	2 733	2 648	3.1	Geophysical Laboratory
Ab_1An_2	2 710	2 591	4.4	Geophysical Laboratory
Ab_1An_1	2 679	2 533	5 45	Geophysical Laboratory
Ab_2An_1	2 660	2.483	6.65	Geophysical Laboratory
Ab_3An_1	2.649	2.458	7.2	Geophysical Laboratory
Albite	2 605	2.382	8.55	Geophysical Laboratory
Albite (Tyrol)	2.625	2.373	9.6	Douglas
Orthoclase	2 551	2 351	7.8	Von Wolff
Sanidine (Ischia)	2.597	2 400	7.6	Abich
Adularia (St. Gotthard)	2 575	2 370	7 6	Douglas
Leucite	2 480	2 410	2 8	Douglas
Quartz (low quartz)	2 651	2 203	16.9	Sosman
Sillimanite	3.022	2 53	16 3	Smithsonian Tables
Diopside (artificial)	3.265	2 846	12 8	Smithsonian Tables
Diopside	3.275	2 830	13 6	Larsen
$MgSiO_3$ (artificial, monoclinic)	3.183	2 735	14 1	Smithsonian Tables
Wollastonite	2.906	2 895	0 4	Smithsonian Tables
Enstatite	3.175	2 743	13 6	Larsen
Augite (Guadeloupe)	3.266	2 835	13 2	Deville
Tremolite	2.990	2.780	7 0	Douglas
Actinolite	3 040	2.810	7 6	Douglas
Pargasite	3 109	2.790	10 3	Douglas
Hornblende (Oran)	3 216	2 826	12 1	Deville
Olivine (Fogo)	3 381	2.831	16.3	Deville
Forsterite (artificial)	3.216	.....	.....	Bowen and Andersen
Fayalite (artificial)	4.068	....	......	L. H. Adams
Garnet (Greenland)	3.90	3.05	21.8	Magnus
Grossularite	3.63	2 95	18.7	Magnus
Akermanite (artificial)	2 944	2 955	− 0.4	Ferguson and Buddington
Gehlenite (artificial)	3.038	2.884	5.1	Ferguson and Buddington
$K_2Si_4O_9$ (artificial)	2 335	2.384	− 0.2	Goranson and Kracek

according to George, and the average of obsidian from the Caucasus (*M*), according to Mickey.

At room temperature the average specific gravity of basalt glass (Tilley) is 6.2 per cent less than the average for 71 dolerites and diabases (2.955), and 6.4 per cent less than the average for 98 gabbros, dolerites, and diabases (2.961). The corresponding percentage for diabase, experimentally found by Day, Sosman, and Hostetter, is 7.2. Their specimen was probably a little more salic than the average gabbro-dolerite-diabase of Table 4, and therefore might be expected to give a slightly larger percentage change.

Joly and Poole found eclogite with specific gravity of 3.415 to melt to glass with specific gravity of only 2.746 (room temperature). This means an increase of 24.4 per cent in volume or a decrease of 19.6 per cent in density.[1]

At room temperature the average specific gravity of rhyolite obsidian (Tilley) is 11.1 per cent less than the average specific gravity of granite. The corresponding percentages for two different granites, artificially melted to glass, were found by Douglas to be 7.90 and 9.66. His values may be lower partly because of the loss of volatile matter during the meltings.

Tilley has shown how densities of glasses may vary with the amount of contained water. For his purpose he used three analyzed and "closely comparable" rhyolite glasses of Lipari. From the analyses he also computed the "normative" densities and from these was able to calculate the change of volume in passing from holocrystalline rock to glass. His results (page 290 of his paper) are condensed into the following table.

Glass	Water content, per cent	Density of glass	Hydrous-norm density	Decrease of density, norm to glass, per cent
Rocche Rosse	0 31	2 370	2 622	9.6
Forgia Vecchia	1.01	2 363	2 593	8.9
Monte Pelato	3 35	2 320	2 485	6.6

A good average figure for the decrease of specific gravity in passing from granite to obsidian at room temperature thus appears to be 10 per cent.

For comparison, and to facilitate checking the values given for rocks, the values of Table 6 are entered.

Porosity.—The International Critical Tables give the following values for the pore space in different rocks (percentages):

[1] J. Joly and J. H. J. Poole, Phil. Mag., vol. 3, 1927, p. 1242.

Rock	Number of determinations	Range of porosity
Granite	5	0 3– 2 6
Gabbro	1	3 0
Basalt	2	0.4– 0.5
Diabase	3	0 2– 1 2
Gneiss	3	2 5– 4 4
Marble	12	0.4– 1 8
Limestone	9	1.0–20 0
Sandstone	13	1 9–22 0

Thermal Expansion.—Accurate values for the rates of thermal dilatation of many important types of rock are not yet in hand. The rates vary from species to species and among individual specimens of the same species. They vary also with temperature. Both rules are illustrated in the following list of mean rates of linear expansion—a list compiled from the data of the International Critical Tables and from Wheeler.[1] These rates (Table 7) are probably close to one-third of the respective rates for volume expansion.

TABLE 7.—LINEAR THERMAL EXPANSION
(Millionths per 1°C.)

Rock	20°–100°	100°–200°	200°–300°
Semicrystalline limestone	22	26	27
Oolitic limestone	4 2	9 6	19
Vermont marble	16	25	29
Carrara marble	8	18	24
Belgian black marble	4.9	10	14
Quartz monzonite, Westerly	9	14	20
Milford granite	7.6 (0°–100°)	13	
Branford gneissoid granite	7.2 (0°–100°)	17	
Troy granite	6.1 (0°–100°)	12	
Diabase	6 3	9	12

The increase of the coefficients with temperature is analogous with that shown in the specially exact determinations for quartz, for which the true volumetric coefficient is 33.6 at 0°, 50.4 at 250°, and 100 at 500°, all in millionths.[2] Wheeler showed that in actual experiments with rocks the apparent increase of coefficients is largely due to the differential swelling of the component minerals with resulting permanent expansion of the specimens. Thus for diabase (first heating) he obtained the following coefficients of linear expansion (millionths) at the temperatures stated:

[1] N. E. Wheeler, Trans. Roy Soc. Canada, vol. 3 (iv), 1910, p. 19.

[2] R. B. Sosman, The Properties of Silica, New York, 1927, p. 362.

100°	6 27
200	8 98
300	12 34
400	16 3
500	23 3
600	37 4
700	21 0
800	12.66
900	9 42
1000	7.18

Clearly these coefficients cannot be directly used for estimating the thermal expansion of diabase under rock pressure sufficient to keep closed such cavities as would be produced by differential stresses at the earth's surface. No more than rough estimates of the coefficients for subterranean rocks can yet be made. Such estimates are given in Table 8 (compare also the values given in Chapter XII).

TABLE 8:—MEAN RATES OF VOLUMETRIC EXPANSION

Material (at low pressure)	Temperature interval	Holocrystalline	Vitreous
Granitic material	0°– 500°	45×10^{-6}	30×10^{-6}
Basaltic material.	0 –1000	25	35
Quartz.....	0 – 500	52	1.7
Crown glass...	0 – 100	....	27
Cast iron.	0 – 500	32	

Experiment further shows that at high pressure the thermal expansion of materials like rocks and glasses decreases with increasing temperature.[1]

Compressibility, Rigidity, Poisson's Ratio.—Igneous action is controlled by the composition and physical condition of the earth's interior. Its diagnosis is now depending largely upon the proper correlation of the velocities of earthquake waves at the different depths with the laboratory (high-pressure) measurement of the elastic properties of rock matter. By the usual method the cubic compressibility, rigidity, and Poisson's ratio (lateral extension of a column of the rock under uniform linear stress, divided by the longitudinal shortening, per unit of length) are measured by employing large increments of pressure. Thus the *mean compressibility, mean rigidity,* and *mean Poisson's ratio* are directly determined for each of these increments. Thence the *true* values for a given pressure are obtained. The results are expressed in bars, a bar being one million dynes per square centimeter, and equal to 1.0197 kilograms per square centimeter, or about 99 per cent of an atmosphere as ordinarily defined.

[1] P. W. Bridgman, Proc. Amer. Acad. Arts and Sciences, vol. 66, 1931, p. 226.

For rocks the best measurements with moderate increments of pressure are those of Zisman (1 to 800 bars) and Adams and Coker (usually 70 to 600 bars).[1] Their results are summarized in Tables 9*a*, 9*b*, and 9*c*. Zisman's specimens exposed directly to the kerosene that transmitted pressure (the "uncovered" specimens) usually showed much smaller compressibility than the same specimens when covered with thin, closely fitting, leak-proof envelopes of copper foil. His experience resembles that of Adams and Williamson. Another noteworthy feature, especially of "covered" granite, French Creek norite, and marble, is the rapidity of the change of compressibility with the first increments of pressure. Table 9*b* illustrates some departure of even plutonic rocks from perfect isotropy, a characteristic more pronounced in the marble and still more in the gneiss, as might be expected. With the more porous rocks Young's modulus and Poisson's ratio are seem to change with remarkable rapidity as the pressure begins to increase in the testing machine.

TABLE 9*a*.—TRUE CUBIC COMPRESSIBILITIES
(Millionths per bar)
(Zisman)

Rock	Pressure at 0 bar:		Pressure at 720 bars (two at 600 bars):	
	Uncovered	Covered	Uncovered	Covered
Granite (Quincy, Massachusetts)	1.96	7 81 (!)	1.70	2.51
Granite (Rockport, Massachusetts)	1.99	9 35 (!)	1 77	2.68
Olivine diabase (Vinal Haven, Maine)	1.49	1 74	1 36 (600 bars)	1 29 (720 bars)
Norite (French Creek, Pennsylvania)	1 43	6 02 (!)	1 28	1 55
Norite (Sudbury, Ontario) . . .	1 67	3 21	1 62	1.66
Obsidian (Lipari Islands).	3 02	3.05	3 02	3 05
Orthogneiss (Pelham, Massachusetts)—parallel to schistosity. . .	2 11	. . . . . .	1.69	
Marble (Proctor, Vermont) .	1.42	18 4 (!)	1.24	1 53 (600 bars)

[1] W. A. Zisman, hitherto unpublished measurements in Professor P. W. Bridgman's laboratory at Harvard University. F. D. Adams and E. G. Coker, Pub. 46, Carnegie Inst. of Washington, 1906.

TABLE 9b.—YOUNG'S MODULUS (E) AND POISSON'S RATIO (σ)
(Zisman)

Rock	Tested cylinders indicated by letters a to c	Mean stress (bars)	$E \times 10^{-11}$	σ
Granite, Quincy (density, 2 64)	a	11 55	3 48 4 70	
	b, ⊥ to a	11 55	3 45 4 63	0 092 .130
Granite, Rockport (density, 2 63)	a	11 55	3 54 4.26	.091 .011
	b, ⊥ to a	11 55	3 95 4 39	.082 .103
Olivine diabase, Vinal Haven (density, 2 96)	a	11 55	10 2 10.2	.257 .257
	b, ⊥ to a	11 55	10.25 10.0	244 .244
	c, ⊥ to a and b	11 55	10.2 10.0	261 .261
Norite, French Creek (density, 3 05)	a	11 55	7.27 7.67	154 .160
	b, ⊥ to a	11 55	5.84 6.15	108 129
	c, ⊥ to a and b	11 55	6 72 7 03	141 • 146
Norite, Sudbury (density, 2.85)	a	36	8 07	212
	b, ⊥ to a	36	7.96	.224
	c, ⊥ to a and b	36	8 05	
Orthogneiss, Pelham (density, 2.64)	a, cut perpendicular to schistosity	0 9	0 328 (!) 0 43 (!)	.0283 (!) 0283 (!)
	b, ⊥ to a	11 55	1 42 2 20	
	c, ⊥ to a and b	11 55	1 68 2 55	.082 (!) .139
Marble, Proctor (density, 2 71)	a, cut perpendicular to apparent bedding	11 55	2 32 3 99	.099 (!) .179
	b, ⊥ to a	11 55	3 43 4 60	134 .180
	c, ⊥ to a and b	11 55	3 83 4 95	.142 .209

TABLE 9c.—MEAN ELASTICITIES
(Adams and Coker)

Rock	Cubic compressibility, millionths per bar	Bulk modulus, dynes/sq. cm	Rigidity modulus, dynes/sq. cm	Poisson's ratio	Young's modulus, dynes/sq. cm.
Average of seven granites.	3.30	3.03×10^{11}	2.067×10^{11}	.222	5.05×10^{11}
One nephelite syenite	2.33	4.29	2.505	.256	6.29
One anorthosite	1.74	5.76	3.275	.262	8.25
One essexite	2.15	4.65	2.67	.258	6.71
One gabbro	1.52	6.59	4.38	.219	10.80
One diabase	1.36	7.33	3.70	.284	9.49
Average of four marbles	2.27	4.40	2.43	.267	6.06
One limestone	2.36	4.25	2.50	.252	6.35
Plate glass	2.25	4.44	2.96	.227	7.24

Table 10 gives true compressibilities, compiled chiefly from experimental results of L. H. Adams and Williamson, L. H. Adams and Gibson, and Bridgman, all using pressures up to 12,000 bars or about 12,000 kilograms per centimeter[1]. Adams and Gibson measured the mean compressibility of basalt glass between 2000 and 12,000 bars and found 1.45×10^{-6} per bar, a considerably higher value than that obtained by Bridgman, whose specimen was likewise from Kilauea, Hawaii. According to Adams and Gibson, the average measured compressibility of three eclogites at 7000 bars is 0.80×10^{-6}.[1]

TABLE 10.—TRUE CUBIC COMPRESSIBILITY
(Millionths per bar)

m, measured directly. *c*, calculated from compressibility of constituent minerals. *Bracketed values*, obtained by extrapolation, interpolation, or correction for the "statistical" change of compressibility.

Rocks	At 1 bar	At 2,000 bars	At 10,000 bars	At 15,000 bars
Granite (A. and W.):				
Stone Mountain	....	*m*, 1.96	*m*, 1.81	
Stone Mountain	.....	*c*, 2.02	*c*, 1.79	
Washington	.....	*m*, 2.27	*m*, 1.76	
Washington	....	*c*, 2.04	*c*, 1.83	
Westerly	.....	*m*, 1.99	*m*, 1.87	
Westerly	...	*c*, 2.07	*c*, 1.84	
Granodiorite (A. and W.)	......	*c*, 1.82	*c*, 1.62	
Diorite (A. and W.)	......	*c*, 1.61	*c*, 1.45	
Gabbro (A. and W.)	.....	*c*, 1.20	*c*, 1.12	
Diabase, quartz free (A. and G.).				
Maryland	...	*m*, 1.23	*m*, 1.07	
Maryland	....	....	*c*, 1.07	(*c*, 1.02)
Palisades	.....	*m*, 1.54	*m*, 1.30	

[1] L. H. Adams and E. D. Williamson, Jour. Franklin Inst., vol. 195, 1923, p. 520; Smithsonian Rep. for 1923, p. 241.; Jour. Washington Acad. Sciences, vol. 21, 1931, p. 381. L. H. Adams and R. E. Gibson, Proc. Nat. Acad. Sciences, vol. 12, 1926, p. 275, and vol. 15, 1929, p. 713. P. W. Bridgman, Amer. Jour. Science, vol. 7, 1924, p. 81; vol. 10, 1925, p. 359; vol. 15, 1928, p. 287. R. B. Sosman, The Properties of Silica, New York, 1927, p. 427. L. H. Adams, Gerlands Beitr. z. Geophysik, vol. 31, 1931, p. 315.

TABLE 10.—TRUE CUBIC COMPRESSIBILITY.—(*Continued*)

Rocks	At 1 bar	At 2,000 bars	At 10,000 bars	At 15,000 bars
Palisades			*c*, 1.16	(*c*, 1 09)
Sudbury		*m*, 1 37	*m*, 1.25	
Sudbury			*c*, 1 16	(*c*, 1.08)
Quartz-bearing diabase, Whin Sill (A. and G.)		*m*, 1.70	*m*, 1 26	
Quartz-bearing diabase, Whin Sill (A and G.)			*c*, 1 17	(*c*, 1 09)
Diabasic basalt (P.W.B)	*m*, 1 59	*m*, 1 54	*m*, 1 33	(*m*, 1.19)
Average crystalline plateau basalt (A. and G)			*c*, 1.13	(*c*, 1 06)
Basalt glass, Kilauea (20 per cent devitrified) at 75° (P W B)	*m*, 1 40	*m*, 1.36	*m*, 1 22	(*m*, 1 13)
Obsidian, Yellowstone Park (A and G.)	*m*, 2 85	*m*, 2.83	*m*, 2 75	(*m*, 2 70)
Pyroxenite (A. and W.)	(*c*, 1 1)	*c*, 1 03	*c*, 0 96	(*c*, 0 92)
Dunite (A. and G)	(*c*, 0 85)	(*c*, 0 84)	(*c*, 0 79)	(*c*, 0 76)
Stony meteorite (L H.A.)	(*c*, 0 85)	(*c*, 0 84)	(*c*, 0 78)	(*c*, 0 76)

Minerals	At 1 bar	At 2,000 bars	At 10,000 bars	At 15,000 bars
Quartz (A. and G.)	*m*, 2 70	*m*, 2.61	*m*, 2 27	
Microcline (A and W.)	*m*, 1 90	*m*, 1 86	*m*, 1 66	(*m*, 1.55)
Oligoclase, Ab_{78} (A and G)	*m*, 1 74	*m*, 1 70	*m*, 1 54	(*m*, 1.44)
Labradorite, Ab_{48} (A. and G)	*m*, 1 48	*m*, 1 44	*m*, 1 28	(*m*, 1 18)
Labradorite, Ab_{33} (A and G)	*m* (1 32)	*m* (1 30)	(1 20)	(1 14)
Diopside (A. and G)	(1 13)	(1 11)	(1 03)	(0 98)
Augite (A and G)	(1 07)	(1 05)	(0 98)	(0 94)
Enstatite (A. and G)	(1 06)	(1.04)	(0 97)	(0 93)
Hypersthene (A. and G.)	(1 04)	(1 02)	(0 95)	(0 91)
Olivine (A. and G.)	(0 85)	(0 84)	(0.79)	(0 76)
Forsterite (L H.A.)	(0 82)	*m*, 0 81	*m*, 0 75	(*m*, 0 73)
Fayalite (L.H A)	(0.96)	*m*, 0 94	*m*, 0 86	(*m*, 0 84)
Garnet, almandite (A. and G)	(0 60)	(0 59)	(0 56)	(0 54)
Magnetite (A. and G.)	0 55	(0 54)	(0 51)	(0 49)

For comparison:				
Pure iron (P W.B.)	*m*, 0 59	*m*, 0 58	*m*, 0.55	
Silica glass at low temperature (A. and G)	*m*, 2 69	*m*, 2.77	*m*, 3.10	
Silica glass at low temperature (P.W.B.)	*m*, 2 70	*m*, 2 77	*m*, 3 06	

Table 10*a* gives the computed densities of four rock types in the crystalline and vitreous states and at different temperatures and pressures, the rate of thermal expansion at the higher pressure being assumed as two-thirds of that at 1 bar.

TABLE 10*a*.—DENSITIES OF ROCK AND GLASS UNDER PRESSURE

	Crystalline at 20°	Vitreous at 20°	Vitreous at 1400°
Granite at 1 bar	2 60	2 34	2.25
Granite at 17,000 bars	2.68	2 46	2.40
Gabbro at 1 bar	3.00	2.82	2.68
Gabbro at 17,000 bars	3 05	2 87	2 78
Plateau basalt at 1 bar	3.02	2.84	2.70
Plateau basalt at 17,000 bars	3.07	2.89	2.80
Peridotite at 1 bar	3 28	2 87	2 73
Peridotite at 17,000 bars	3.32	2 91	2 82

Bridgman has recently made evident the slightness of the effect of pressure on the *rigidity* of metals and artificial glasses, and doubtless it is so small for rocks, including rock glass, that it may be ignored in most geological problems which are not concerned with short-period stresses.[1] A given increment of all-sided pressure changes rigidity even less than it changes the compressibility of metals and glass.

His experiments confirm the view that pressure changes but little the value of *Poisson's ratio* for deep-seated rocks. In fact, for the low stresses associated with the transmission of earthquake waves this ratio is approximately 0.27 for all depths in the earth between the 60-kilometer level and the 2900-kilometer level (major discontinuity).

Temperature has apparently small effect on the compressibility of rocks. Bridgman did find measurable differences when the temperature of his rocks was raised from 30° to 75°, but the percentage difference must decrease with increasing depth below the earth's surface.

Evidently a large change of density, due to change of all-sided pressure or to change of temperature, is not to be expected unless the pressure changes by thousands of atmospheres or the temperature changes by hundreds of degrees. However, for some major problems of geology the effects of compression or decompression and heating at great depths in the earth are not negligible.

Thermal Conductivity and Diffusivity.—The rate at which heat flows in rocks (thermal conductivity) and the rate at which temperature flows in them (thermometric conductivity or diffusivity) are naturally of high importance in the theory of petrogenesis. Some of the best data are here assembled.

The accurate measurement of absolute conductivity and therefore also of absolute diffusivity (conductivity divided by the product of density and specific heat) is more difficult than the determination of relative conductivities. Moreover, special weight should be given to measurements made by the same observer, using one method only. Hence, old as it is, Lees' table of relative conductivities of various rocks retains value (Table 11).[2]

TABLE 11

Rock	Relative Conductivity
Marble, Pyrenees	100
Granite	80.4
Carrara marble	76.9
Marble, Italy	76.3

[1] P. W. Bridgman, Proc. Amer. Acad. Arts and Sciences, vol. 63, 1929, p. 401, and vol. 64, 1929, p. 39.

[2] C. H. Lees, Phil. Trans. Roy. Soc. London, vol. 183, A, 1892, p. 481.

TABLE 11.—(*Continued*)

Rock	Relative Conductivity
Basalt, Oberstein	72 6
Sandstone, fine-grained	72.1
Granite, Thuringen	71.3
Red gneiss, Tharandt	69.6
Nephelite basalt	69 0
Gneiss, Tharandt	67.3
Slate (direction relative to cleavage not given)	53 7
Clay slate	46 9
Clay	27.5

Koenigsberger and Mühlberg, Tadokoro, Poole, Friedlaender, Eucken, and Bridgman have supplied noteworthy results of experiments on the absolute conductivities of rocks and rock minerals (Table 12).[1]

TABLE 12.—THERMAL CONDUCTIVITIES
(C.g.s. units; room temperature unless otherwise indicated)

Granite:	
Tadokoro, specimen 1	6.01×10^{-3}
Tadokoro, specimen 2	5 13
Poole (75°)	5.17
Andesite (holocrystalline):	
Koenigsberger and Mühlberg	3.06
Olivine-pyroxene andesite:	
Tadokoro	3 07
Porphyry:	
Koenigsberger and Mühlberg	5.47
Augite porphyrite:	
Tadokoro	3.71
Hornblende porphyrite:	
Tadokoro	4.32
Diorite:	
Tadokoro	5.53
Basalt:	
Tadokoro	3 45
Bridgman (30°)	4.04
Poole (75°)	4.09

[1] J. Koenigsberger and M. Mühlberg, Neues Jahrb. f. Mineralogie, etc., B.B. 31, 1911, p. 140. Y. Tadokoro, Science Rep., Tôhoku Imper. Univ., vol. 10, No. 5, 1921, p. 339. H. H. Poole, Phil. Mag., vol. 46, 1923, p. 408, and vol. 27, 1914, p. 58. I. Friedlaender, Gerlands Beitr. z. Geophysik, vol. 11, 1912, p. 85. A. Eucken, Ann. d. Physik, vol. 34, 1911, p. 215. P. W. Bridgman, Amer. Jour. Science, vol. 7, 1924, p. 89.

TABLE 12.—THERMAL CONDUCTIVITIES.—(*Continued*)

Leucite tephrite (Vesuvius):	
Friedlaender, specimen 1	4.36
Friedlaender, specimen 2	4.74
Friedlaender, specimen 3	4.33
Hornblende gabbro:	
Tadokoro	4.16
Amphibolite:	
Tadokoro	4.82
Obsidian (Lipari):	
Koenigsberger and Muhlberg	1.92
Artificial glass:	
Tadokoro	2.60
Range of six kinds (Smithsonian Tables)	1.80–2.80
Gneiss:	
Koenigsberger and Mühlberg (feldspar rich)	5.50
Koenigsberger and Muhlberg (biotite rich)	6.75
Koenigsberger and Muhlberg (hornblendic)	4.30
Koenigsberger and Muhlberg (paragneiss)	4.68
Weber (0°)	5.78
Weber (100°)	4.16
Phyllite:	
Koenigsberger and Mühlberg	6.77
Quartzite:	
Tadokoro	12.31
Quartz (30°):	
Eucken (parallel to axis)	29.4
Eucken (at right angle to axis)	15.65
Limestone:	
Koenigsberger and Mühlberg	4.93
Tadokoro	6.07
Bridgman (Solenhofen limestone at 30°)	5.23
Poole (40°)	4.60
Marble:	
Koenigsberger and Mühlberg	5.20
Tadokoro	5.55
Eucken	7.14
Calcite (at right angle to axis):	
Eucken	9.4
Lees	8.4

Schulz has made a useful compilation of experimental results on the conductivity of different rocks. From his publication Table 13 is

extracted; it illustrates the considerable excess of the conductivity along planes of schistosity or bedding over that at right angles thereto.[1]

TABLE 13.—RATIO OF THERMAL CONDUCTIVITY ALONG SCHISTOSITY OR BEDDING TO THE CONDUCTIVITY ACROSS THE STRUCTURE

Rock	Average ratio	Number of specimens averaged
Protogine..........	1 12	3
Gneissic diorite..	1 12	1
Sandstone	1 20	18
Limestone..	1 25	8
Marl..	1 28	2
Clay	1 23	2
Clay slate and phyllite	1 24	48
Gneiss	1 15	20
Mica schist	1.54	3

As a rule, minerals and rocks, like metals, decrease in conductivity as their temperature rises. For example, quartz, parallel to its chief axis, has conductivities of 0.032, 0.0255, and 0.021 at the respective temperatures of 0°, 50°, and 100°. Kelvin and Murray found that the mean conductivity of slate (with lines of flux parallel to the cleavage) within the temperature range of 123° to 202°C. was 91 per cent of that within the range 50° to 123°; also that the mean conductivity of granite at 145° to 214° was 88 per cent of its value at 81° to 145°.[2] Poole determined the conductivity of a limestone to be 0.0046 at 40° and only 0.00322 at 550°C.; granite illustrates the same principle, with conductivity equal to 0.00517 at 75° and 0.00395 at 537°, though much of this change was due to the cracking of the rock as it was heated.[3]

On the other hand, silicate glasses, like many other amorphous substances, exhibit decrease of resistance to the flow of heat as the

[1] K. Schulz, Fortschr. d. Mineralogie, etc., vol. 9, 1924, p. 330.

[2] Lord Kelvin and J. R. E. Murray, Proc. Roy. Soc. London, vol. 58, 1895, p. 162.

[3] H. H. Poole, Phil. Mag., vol. 24, 1912, p. 45; also *ibid.*, vol. 27, 1914, p. 58, and vol. 46, 1923, p. 408. Compare Weber's experimental results on gneiss, quoted in the Landolt-Börnstein Tabellen and in the International Critical Tables; J. Koenigsberger, Phys. Zeit., vol. 7, 1906, p. 297; A. Eucken, Annalen d. Physik, vol. 34, 1911, p. 215. S. Konno, Phil. Mag., vol. 40, 1920, p. 548.

Fibrous, powdered, and other cellular materials become notably more conductive as the temperature rises. Examples are laminated and corrugated asbestos, magnesia brick, diatomaceous powder, cotton, silk, wool, pulverized cork, and infusorial earth (see L. S. Marks, Mechanical Engineers' Handbook, New York, 3d ed., 1930, p. 398). The systematic contrast with the rocks mentioned in the text may be connected with the difference in compactness.

temperature rises. Thus vitreous silica has a conductivity of 0.0034 at 0° and about 0.0045 at 100°. For ordinary glass, Lees found a mean percentage increase of 0.0025 in the conductivity for each degree of rise of temperature from 35° to 60°. Analogous results were obtained for artificial glasses by Eucken.[1] The rate of increase for pyrex glass diminishes greatly as the temperature rises. Stephens's curve gives its conductivity at 0°C., 250°C., 1000°C. and 1500°C. (extrapolation from 250° upwards) as respectively 0.00246, 0.00315, 0.00409, and 0.00444.[2]

Pressure affects the conductivity of rocks only slightly. Lees was not able to detect a sensible change in the conductivity of granite or marble as the hydrostatic pressure increased to 800 pounds per square inch, though glass showed a slight increase in that property.[3] For pyrex glass and certain rocks, Bridgman obtained the results shown in Table 14.[4]

TABLE 14—THERMAL CONDUCTIVITY AND PRESSURE

Substance	Conductivity at 1 kg/cm² (30°C)	Percentage increase of conductivity for 1000 kg/cm²
Pyrex glass	0 00261	0 38
Basalt	0 00404	0.47
Limestone, Solenhofen	0 00523	0.1
Talc	0 00733	1.57
Pipestone	0 00438	3.0
NaCl	0 00880	3.6

It seems clear that, down to the depth of 100 kilometers within the earth, the pressure effect on the conductivity is likely to be much smaller than the effect due to the increase of temperature with the depth, the two effects probably being of opposite sign in the upper half of the earth shell involved. Further experiments, especially where high temperatures are introduced, are urgently needed to facilitate more accurate deduction regarding the thermal history of the earth and of the larger bodies intruded into its crust.

[1] See R. B. Sosman, The Properties of Silica, New York, 1927, p. 417; C. H. Lees, Phil. Trans. Roy. Soc. London, vol. 191, A, 1898, p. 418; A. Eucken, *op. cit.*, p. 220. Compare also A. H. Davis on the conductivity of liquids (Phil. Mag., vol. 47, 1924, p. 972); International Critical Tables, section on the relation between conductivity and temperature for glasses, fire clay, carbon, graphite, and silica brick.

[2] R. W. B. Stephens, Phil. Mag., vol. 14, 1932, p. 897.

[3] C. H. Lees, Memoirs Manchester Lit. and Phil. Soc., vol. 43, No. 8, 1899, p. 1.

[4] P. W. Bridgman, Amer. Jour. Science, vol. 7, 1924, p. 89; here also new results on conductivities at two different temperatures.

In any case rock, rock glass, and magma must be considered to be poor conductors of heat. An illustration, ready to hand, has been furnished by Koenigsberger. He computed the time needed to lower the initially uniform temperature of an extensive, thick sheet of acid rock, exposed to the air, from an initial value of 1100° to the temperature of 750°—at five different depths, here stated:

Depth, Meters	Time Required
1	12 days
10	3 years
100	300 years
1,000	30,000 years
10,000	3,000,000 years

Heat Capacity.—The true specific heats or true heat capacities of rocks at widely different temperatures have not been determined with needed accuracy. Precise work has, however, been done by White on silica and silicate minerals, and his results (Table 15) are well qualified to control thought about the thermal energy represented in rocks and magmas.[1]

TABLE 15.—TRUE HEAT CAPACITIES AT VARIOUS TEMPERATURES
(Gram-calories per gram)

Substance	0°	500°	1000°	1300°
Silica glass	0.166	0.266	0 292	0.316
Quartz	.167	294	.285	
Anorthite	.174	.260	.286	.318
Albite	177	.269	.294	
Microcline	.171	.258	.279	
Microcline glass	.176	.265	.299	
Pseudowollastonite	.171	.243	262	.272
Diopside	.176	.262	.284	
Artificial amphibole	.185	.279	.304	
Crystalline diabase or basalt	*ca.* .185	*ca.* .250	*ca.* .270	
Vitreous diabase or basalt	*ca.* .185	....	....	*ca.* .350

The values shown in the last two horizontal rows of Table 15 are based on the experiments of Barus and their discussion by Vogt.[2] Their accuracy is doubtless not so great as that of the figures for the crystals and glasses but suffices for most purposes of the petrologist.

[1] W. P. White, Amer. Jour. Science, vol. 47, 1919, p. 19. The true specific heats of silica glass at 1000° and 1300°, given in Table 15, were obtained from R. B. Sosman, The Properties of Silica, New York, 1927, p. 314.

[2] C. Barus, Phil. Mag., vol. 42, 1891, p. 498, and Bull. 103, U.S. Geol. Survey, 1903. J. H. L. Vogt, Die Silikatschmelzungen, Christiania (Oslo), part 2, 1904, p. 45. *Cf.* K. Schulz, Centralbl. f. Mineralogie, etc 1911, p. 632; A. Wigand, Annalen d. Physik, vol. 22, 1907, p. 64.

Latent Heat.—More difficult is the measurement of the latent heat of rock glasses and magmas. For quartz (high quartz to liquid) it appears to be about 50 calories per gram, but this estimate is only rough (Mulert's estimate, 37 calories). The values for various slags range between 45 and 120 calories per gram. Those for cristobalite, $K_2Si_4O_9$, albite, anorthite, and diopside, are close to 30.5, 35, 49, 104, and 108 calories, respectively. Vogt gave for akermanite 90 calories and estimated 130 calories for olivine and 125 calories for enstatite, with, for these two, maximum errors of plus or minus 15 per cent. Mulert's figures for eleolite and microcline, 99.8 calories and 83 calories, respectively, may be somewhat in error, but Vogt regarded them as significant. Vogt's estimate for diabase is 90 to 100 calories per gram, a value which is nearly the mean of the latent heat of its minerals. If the same relation holds for other rocks, the latent heats of granite, granodiorite, and quartz monzonite are probably no higher than about 60 calories per gram.[1]

Total Melting Heat.—From Vogt's memoir the following approximate values of total melting heats, reckoned from 0°, have been taken:

	Calories
Diopside	444
Akermanite	404
Anorthite	458
Four slags	376–434
Augite	444
Diabase	400–450

Temperatures of Melting and Crystallization.—Table 16 gives the more reliable (chiefly Geophysical Laboratory of Washington) measurements of the temperatures or temperature intervals at which rock-forming crystals and their artificial analogues melt. Table 16*a* gives melting data for rocks.

The melting temperature of a mineral like anorthite or diopside is raised by pressure. The well-known Clausius-Clapeyron equation connecting the change of this temperature with increase of all-sided pressure, per atmosphere, reads as follows:

$$\frac{dT}{dp} = \frac{(V - v) \cdot T}{L} \times 0.024,$$

[1] Leading references on the subject are: R. B. Sosman, The Properties of Silica, New York, 1927, p. 312; J. H. L. Vogt, Die Silikatschmelzlösungen, Oslo, part 2, 1904, pp. 65, 68, 209; N. L. Bowen, Amer. Jour. Science, vol. 35, 1913, p. 599, and The Evolution of the Igneous Rocks, Princeton, 1928, p. 176; O. Mulert, Zeit. f. anorgan. Chemie, vol. 75, 1912, p. 198; W. Eitel, Physikalische Chemie der Silikate, Leipzig, 1929, p. 165. R. W. Goranson and F. C. Kracek, Jour. Phys. Chem., vol. 36, 1932, p. 920. F. C. Kracek, Jour. Amer. Chem. Soc., vol. 52, 1930, p. 1442.

TABLE 16.—MELTING POINTS AND MELTING INTERVALS
(Single crystals)

	Degrees Centigrade
Amphibole group:	
Barkevikite	1080–1125
Hornblende, within range of	1060–1200
Calcite	1340
Carnegieite (artificial)	1526
$CaSiO_3$ (artificial)	1540
Clino-enstatite (artificial—incongruent)	1557
Corundum	2050
Feldspar group:	
Adular	1160–1200
Albite (Ab)	1100
Andesine-labradorite (Ab_1An_1)	1287–1450
Anorthite (An)	1550
Microcline	Below 1200
Orthoclase (incongruent)	1170
Galena	1120
Halite (NaCl)	800
KCl	770
$K_2Si_2O_5$ (artificial)	1041
K_2SiO_3 (artificial)	976
Leucite	1686
Leucite (artificial)	1820
Lime (CaO)	2570
Magnetite	1580
Melilite group:	
Akermanite (artificial)	1458
Gehlenite (artificial)	1590
Na_2SiO_3 (artificial)	1088
Nephelite (Magnet Cove)	Below 1370
Olivine group:	
Fayalite (artificial)	1205
Fayalite (natural)	1207–1217
Forsterite (artificial)	1890
Olivine	1360–1410
Periclase (MgO)	2800
Platinum	1755
Pyroxene group:	
Acmite (artificial—incongruent)	990
Acmite (Quincy, Massachusetts)	975
Augite	1185–1200
Bronzite	1310–1370
Diopside (artificial)	1391
Pyrrhotite	1157–1187
Silica group:	
Cristobalite	1713
Quartz ... Probably below	1470
Tridymite	1670
Sillimanite (incongruent)	1545
Sulphur	119
Wollastonite	1190

TABLE 16a.—TEMPERATURES OF INCIPIENT MELTING AND READY FLOW (Rocks)

Reference	Rock	Fusion begins, degrees Centigrade	Ready flow, degrees Centigrade
1	Palisades diabase	1150	1225
2	Lava, Vesuvius	1103	
2	Lava, Etna	1260	
2	Lava, Stromboli	1207	
2	Basalt, Plateau de Charade, France	1040	
2	Basalt, Réunion	1054	
2	Basalt, Savaii, Samoa	1053	
2	Basalt, Teneriffe	1060	
2	(Basalt glass, Kilauea, softens	1072)	
2	Andesite, Santorin	1098	
3	Rhyolite	...	1260
3	Shap granite	1235	1255
3	Peterhead granite	...	1215
3	Syenite, Plauen	1165	1175
3	Tonalite	...	1150
3	Diorite, Markfield	...	1147
3	Diorite, Guernsey	...	1125
3	Quartz diabase	1085	1105
3	Dolerite, Whin Sill	...	1107
3	Dolerite, Rowley Rag	...	1100
3	Dolerite, Clee Hills	...	1070
3	Andesite, New Zealand	1095	1125
3	Andesite, New Zealand	1097	1100
3	Gabbro	...	1085
4	Granite	Below 700° ("probably at 570°")	In 1 week at 800° becomes half liquid. Corresponding degree of melting for basalt at 1100°.

1. A. L Day, R B. Sosman, and J C. Hostetter, Amer Jour. Science, vol. 37, 1914, p. 29.
2 A. Brun, Recherches sur l'exhalaison volcanique, Geneva, 1911; Arch. des. sci. phys. et nat., Geneva, 1905, sep., p 1
3. J. A. Douglas, Quart. Jour Geol Soc. London, vol. 63, 1907, p 145.
4 J W. Greig, E. S. Shepherd, and H. E. Merwin in Ann. Rep. Director Geophys. Lab. Washington, 1931, p. 77.

where T represents the absolute temperature of melting; p, the pressure; L, the latent heat of melting; and $(V - v)$, the change in volume of 1 gram of the substance on melting.

For diopside the melting point is raised about 4.6° per kilometer of depth in average crust rock.

The formula is not easily applied where pressures greater than those corresponding to depths of a few hundreds of kilometers in the earth are involved, for it is not known at what rates L and $(V - v)$

change with such pressures and temperatures. As a rule L tends to increase with pressure and $(V - v)$ to become smaller, since a vitreous silicate is somewhat more compressible than the crystalline equivalent; this difference decreases as pressure rises.

According to Bridgman's high-pressure experiments, one may well doubt that $(V - v)$ will ever become negative within the earth. At any rate, Tammann's assumption of a maximum melting point for a silicate is not supported by any definite experiments.[1]

The stated formula applies to monovariant systems, those with n components and $n + 1$ phases, and probably gives an approximation to the effect of pressure on the melting temperatures of the common "anchi-eutectic" rocks. On this assumption Holmes, Adams, and Jeffreys have estimated the rate of change for igneous rocks in general at, respectively, 5°, 4°, and 3° per unit of pressure equaling the weight of 1 kilometer of crust rock, though the rate slowly diminishes as the depth becomes great.[2]

The approximate temperatures at which various anhydrous rocks at atmospheric pressure begin to crystallize were estimated by Vogt as follows:[3]

	Degrees Centigrade
Dunite	1500
Other peridotites	1400
Bytownite rock	1475–1500
Labradorite rock	1400–1450
Gabbro and norite	1250
Diorite	1200
Syenite	1100
Granite	1000 (in part a little lower)

[1] See P. W. Bridgman, Phys. Rev., vol. 3, 1914, p. 197; Handbuch der Experimentalphysik, Leipzig, vol. 8, part 2, 1929, p. 363.

[2] A. Holmes, Geol. Mag., vol. 62, 1925, p. 507, where will be found references to the discussions by L. H. Adams and H. Jeffreys. *Cf.* H. E. Boeke (and W. Eitel), Grundlagen der physikalisch-chemischen Petrographie, 2d ed., Berlin, 1923, p. 26; J. Johnston, Jour. Geol., vol. 23, 1915, p. 736; F. von Wolff, Handbuch der Geophysik, edited by B. Gutenberg, Berlin, vol. 3, Lief. 1, 1930, p. 42.

Presumably the Clausius-Clapeyron equation does not apply to rocks which depart widely from eutectic composition. In these cases solubility rather than simple melting controls the change of state with rise of temperature under pressure. Here the relation is given in a theoretical equation, stated by P. W. Bridgman (The Physics of High Pressure, New York, 1931, p. 357). For lack of the experimental data the equation is not now of practical use in the problem as this concerns abnormal rocks.

In any case, calculation by the Clausius-Clapeyron equation can give an idea of the minimum temperature required to keep wholly vitreous one of the standard rocks at moderate depth in the earth.

[3] J. H. L. Vogt, Econ. Geol., vol. 21, 1926, p. 232.

Goranson has succeeded in the difficult task of determining the liquidus curve of granitic magma as a function of the concentration of water. His results are:[1]

Percentage Weight of Water	Temperature ±50°C.
None	1100°
1	1085
2	1060
3	1020
4	960
5	875
6	760
6.5	680
7	600

At the pressure of 980 bars and temperature of about 700°, his charge of liquid granite had 6.3 per cent of water in solution. He found that dry granite begins to melt at 900° to 950°.

Volcanic Temperatures.—Table 17 gives some of the more reliable estimates of the maximum temperatures at volcanic vents of the central type. Compare Plate II.

TABLE 17.—TEMPERATURES AT VOLCANIC VENTS

Authority*	Locality	Maximum temperature of lava, degrees Centigrade
Day and Shepherd	Kilauea	1185
Jaggar (see Fig. 125)	Kilauea	1200
Brun	Vesuvius (1904 lava)	1100
Perret	Vesuvius (1913 lava)	1200
Brun	Stromboli (1901 lava)	1150
Bartoli	Etna (1892 lava)	1060
H. Philipp (per Tyrrell)	Etna (1892 lava)	1300
Kotō	Sakura-jima (1914 lava)	1048
Tsuboi	Oshima	"Probably as low as 1200–1300"

* A L. Day and E. S. Shepherd, Bull. Geol Soc. America, vol. 24, 1913, p. 601. T. A. Jaggar, Amer. Jour Science, vol 44, 1917, p. 214 A. Brun, Le Globe, Geneva, vol. 46, 1907, sep. p. 5; Recherches sur l'exhalaison volcanique, Geneva, 1911, p 37 F. A. Perret, Pub. 339, Carnegie Inst. of Washington, 1924, p. 120. A. Bartoli, in A. Ricco and S Arcidiacono, Boll. Soc Met. Italiana, vol. 12, 1904 p. 11. G. W. Tyrrell, Volcanoes, London, 1931, p. 135. B Kotō, Jour Coll. Sci. Univ Tokyo, vol. 38, 1916, art. 3, p. 112 S Tsuboi, *ibid.*, vol. 43, 1920, p. 145.

Actual temperatures of magmas, indirectly inferred from the effects of heat on minerals and rocks, are given in Chapter XIII, page 303.

Radioactivity of Rocks.—That practically every rock at the earth's surface is a furnace "fired" by atomic decay seems established, and most geophysicists assume that the thermal efficiency of a mass of rock would not be affected by burial of the mass, for neither high pres-

[1] R. W. Goranson, Amer. Jour. Science, vol. 22, 1931, p. 481.

sure nor high temperature appears to have any effect on the rate of atomic break-up. As far as known, important radioactivity is confined to the heavy elements of the uranium and thorium families and in subordinate degree to the lighter potassium.[1]

The radioactive heating varies among the rock types roughly in proportion to the content of radium. Estimates of the amount of

TABLE 18.—RADIUM IN ROCKS (AVERAGES)

	Radium, Gram per Gram
Granite:	
World average:	
Goranson (176 specimens)	2 7 $\times 10^{-12}$
Holmes	3 0
International Critical Tables (63 specimens)	2.7
Jeffreys	4.1
Joly	3.0
Strutt (Eve and McIntosh)	2 8
Eastern North America (Piggot—13 specimens)	1.4
Leinster, Ireland (International Critical Tables—28 specimens)	1 7
Germany (*ibid.*—7 specimens)	9 8
Mysore, India (*ibid.*—11 specimens)	1 03
Charnockite (*ibid.*—3 specimens)	.09
Dutch East Indies (*ibid.*—5 specimens)	4.9
Basalt:	
World average:	
Goranson (53 specimens)	1.185
Jeffreys	1.6
Kirsch	1.4
Island basalt, Joly and Poole:	
Atlantic islands	1 31
Indian Ocean islands	86
Pacific Ocean islands	1 09
Average of all	1.15
Hawaiian lavas, basic (Piggot—13 specimens)	.96
Plateau basalt:	
Holmes	.75
Poole	75
Jeffreys	1.0
Diabase, dolerite, gabbro:	
World average, Goranson	1 3

[1] A. Holmes (verbal communication) now agrees that potassium is only one-fifth to one-tenth as radioactive as had been reported by A. Holmes and R. W. Lawson.

radium in granites and rocks of basaltic composition are specially instructive (Table 18).[1]

According to Kirsch the chief families of radioactive elements in equilibrium produce heat at the following rates in calories per gram:

	Uranium	Thorium
Per second	2.5×10^{-8}	$6\ 8 \times 10^{-9}$
Per year	.79	.21

Joly and Poole (1927) give, per cubic centimeter of granite, the rates of heat production by the uranium and thorium families: respectively, 44.8×10^{-14} and 35.2×10^{-14} calory per second. Adding the approximate value for the potassium, 5×10^{-14}, we have a total of

TABLE 19.—APPROXIMATE RATES OF RADIOACTIVE PRODUCTION OF HEAT
(Calories per gram per second)

Granite:	
World average:	
Goranson	24×10^{-14}
Holmes (1929)	35
Joly and Poole	30
Kirsch	31
Oldest Finnish, Holmes	20
Sial in general, Kirsch	25
Basalt:	
World average:	
Goranson	10
Kirsch	14
Plateau basalt:	
Holmes (1929)	8
Joly and Poole	8
Diabase (dolerite), world:	
Goranson	10
Kirsch	8
"Gabbroid substratum," Kirsch	9
Peridotite	6
Dunite	4
Stony meteorites	4

[1] Among the many papers and memoirs already published on the radioactivity of rocks and particularly on the subject of this section, the following are noted:

A. Holmes, Phil. Mag., vol. 2, 1926, p. 1225; Trans. Geol. Soc. Glasgow, vol. 18, 1929, p. 570. A. Holmes and R. W. Lawson, Phil. Mag. vol. 2, 1926, p. 1218. J. Joly and J. H. J. Poole, *ibid.*, vol. 48, 1924, p. 819. J. Joly and J. H. J. Poole, *ibid.*, vol. 3, 1927, p. 1233. J. H. J. Poole, *ibid.*, p. 1246. A. Holmes, Geol. Mag., vol. 62, 1925, p. 533, and vol. 63, 1926, p. 317. G. Kirsch, Geologie und Radioaktivitat, Wien, 1928, p. 42; Handbuch d. Experimentalen Physik, vol. 25, Teil 2, 1931, p. 41. C. S. Piggot, Amer. Jour. Science, vol. 21, 1931, p. 28; vol. 22, 1931, p. 1. R. W. Goranson, *ibid.*, vol. 16, 1928, p. 101. H. Jeffreys, The Earth, 2d ed., Cambridge, Eng., 1929, p. 143.

85×10^{-14} calory per cubic centimeter per second or 32×10^{-14} calory per gram per second.

The corresponding value for oceanic basalt is 12×10^{-14} calory per gram per second, and for plateau basalt 8×10^{-14} calory per gram per second.

For comparison, other estimates of heat production are entered in Table 19, the actual figures of which are based upon the assumption that the radioactivity of potassium is one-seventh of the value given by Holmes and Lawson.

Strength: Compressive, Shearing, Tensile.—Many problems concerning igneous rocks and magmas can not be seriously attacked without knowledge of the approximate strengths of rocks, both igneous and sedimentary. For general orientation the following data, copied from standard handbooks, will suffice.

AVERAGE ULTIMATE STRENGTHS*
(Kilograms per square centimeter)

Substance	Measured by Watertown Arsenal		Measured by Bauschinger	
	Compressive	Shearing	Compressive	Shearing
Granite	1420	160	1370	100
Marble	885	90	560	45
Limestone	630	100	810	60
Sandstone	880	120	810	50

* Smithsonian Physical Tables, 7th ed, 1920, p. 92.

AVERAGE STRENGTHS†
(Kilograms per square centimeter)

Substance	Compressive	Shearing	Tensile
Granite	1000–2800	150–300	30–50
Marble	800–1500	100–300	30–90
Limestone	400–1400	100–200	30–60
Syenite	1000–2000		
Granodiorite	1000–1500		
Diorite	1000–2500		
Gabbro	1000–1900		
Diabase	1800–2700		
Basalt	2000–3500		

† International Critical Tables, New York, vol. 2, 1927.

The values in the two tables refer to specimens tested under a lateral pressure of 1 atmosphere. The same materials under high, all-sided pressure would have much greater compressive strength. Though the conditions of stress in the classic high-pressure experiments of Adams and of Bridgman were different, they prove the case.[1]

[1] F. D. Adams, Jour. Geol., vol. 20, 1912, p. 97. P. W. Bridgman, Amer. Jour. Science, vol. 45, 1918, p. 243.

Adams first studied the collapse of small cavities in rocks subjected to all-sided pressure and concluded

> . . . that granite under the conditions of cubic compression which obtain in the earth, will sustain a load of about 100 tons to the square inch [about 14,000 bars or kilograms per square centimeter], that is to say, a load rather more than seven times as great as the crushing load of the granite at the surface of the earth under the conditions of the ordinary laboratory test.

Increasing the temperature appropriately, Adams further experimented and found "that empty cavities may exist in granite to a depth of at least 11 miles," where the pressure is at least 4700 bars.

Bridgman (page 261 of his paper), using a different method, found that all-sided pressure at room temperature increased the strength of granite and limestone, but at a rate less than half that found by Adams. Much more rapid was the increase of strength of glass with all-sided pressure, as shown by the failure of small cylindrical and spherical cavities to close at pressures reaching even 24,000 atmospheres. When under the same conditions enough pressure was applied to cause the rupture of an andesite, the compressive stress at the interior of the specimen had then reached the value of 16,000 atmospheres, while the compressive strength as ordinarily stated is measured by the pressure of about 1600 atmospheres.[1]

Experiments by Adams and Bancroft were designed to give results significant in problems relating to orogeny, the development of schistosity, and the rise of magma into the earth's crust.[2] In the words of their summary, "the additional tangential thrust required to induce a pronounced movement in the case of granite and marble" is for

1. Marble at depth of 6.8 km ca. 4,660 kg/cm^2 (4517 atm.).
   Marble at depth of 9.3 km ca. 5,230 kg/cm^2.
2. Granite at depth of 6.8 km ca. 9,730 kg/cm^2.
   Granite at depth of 9.3 km ca. 11,200 kg/cm^2.

Viscosity.—The viscosity of some basic lavas at the moment of eruption is comparable with that of a moderately fluent oil. According to Becker, the 1840 lava of Kilauea flowed 400 meters per hour on a 2-degree slope, or one twenty-fourth as fast as water would flow on the same slope. This indicates a kinetic viscosity only sixty times that of water and comparable with that of olive oil.[3] For comparison Table 20 may be consulted. See Plate II.

[1] P. W. Bridgman, Phil. Mag., July, 1912, p. 72; Amer. Jour. Science, vol. 45, 1918, p. 260.

[2] F. D. Adams and J. A. Bancroft, Jour. Geol., vol. 25, 1917, p. 636.

[3] G. F. Becker, Amer. Jour. Science, vol. 3, 1897, p. 29. H. S. Palmer (Mon. Bull. Hawaiian Volcano Observatory, vol. 15, No. 1, 1927) estimates a viscosity of the Alika lava of Hawaii to have been only eleven to twenty times that of water.

TABLE 20.—VISCOSITIES
(Approximate values)

Substance	Temperature, degrees Centigrade	Absolute viscosity, dynes per square centimeter per unit of velocity gradient	Authority
Water	20	0 01	Clark's tables
Slag	1500	5	Feild
Slag	1300	20	Feild
Glycerine	20	8 5	Clark's tables
Shoemaker's wax	8	4.7×10^6	Trouton and Andrews
Gelatine	*ca.* 20	$10^6 - 10^8$	Schweydar
Marine glue	25	2×10^8	Barus
Pitch	8	9.9×10^{10}	Trouton and Andrews
Soda glass	710	$4\ 5 \times 10^{10}$	Trouton and Andrews
Soda glass	660	$2\ 3 \times 10^{11}$	Trouton and Andrews
Soda glass	575	1.1×10^{13}	Trouton and Andrews
Steel	25	$10^{16} - 10^{18}$	Schweydar
Glass	15	Probably infinite	Jeffreys

Temperature control over viscosity is more familiar than pressure control. Here we can reason only from experimental analogies, such as those supplied by Bridgman. Nevertheless, it seems highly probable that all-sided pressure alone is competent to explain the enormous viscosity of the rock constituting the greater part of the earth's body. The grounds for this statement will be set forth in Chapter IX, where also is given the reason for assuming that the ultimate yielding of earth materials to stress obeys laws which differ widely according to the magnitude of the stress (see page 193).

Other Properties.—A number of additional characteristics of rocks and magmas are considered, more or less quantitatively, in succeeding chapters (see Index). Among the relevant topics are radiation of heat, superheat, conditions for convection, gas solubility, and the retrograde boiling point.

CHAPTER VI

INJECTED BODIES

INTRODUCTION

Some one has said that discussions generally end where they should have begun—with the definition of terms. Accordingly, it is not a mere matter of pedantry if we make a preliminary survey of the kinds of rock bodies with which the petrologist has to deal. Any petrogenetic theory necessarily takes account of the types of form assumed by igneous rocks; their definition to the limit of actual knowledge is a vital aid to accurate thinking. Unfortunately there is no generally accepted classification of either intrusive or extrusive types of form. Yet the universal adoption of a consistent, well-defined scheme of types—a scheme as complete as possible but elastic enough to admit new types when recognized—would give field descriptions and theoretical discussion greater economy of words and more certainty of being thoroughly understood. Moreover, a systematic classification cannot fail to sharpen the eyes of the field observer. A good observer always feels the pressure of the category. He does not describe a given intrusion as merely a "mass" or "area" or "outcrop," if it is possible by mapping and study of contacts to indicate the true form and relations of the body. The use of the term "mass" is justified where the shape and intrusive mechanism are not determinable. Then the body is not to be adequately classified in a genetic system. Yet more definite classification, less negative description, is unquestionably desirable.

On account of their greater volume and deeper significance for petrology, the intrusive bodies will here be treated before the extrusive. Geologists are agreed that for the first group the method of intrusion is the best basis of classification. There are difficulties in the way. Transitional types are found. An intrusive sheet or laccolith is generally continuous with its feeding dike or dikes. Many sheets, dikes, and more irregular bodies pass directly into parent masses called "batholiths." Even the distinction between intrusive and extrusive is obscure where dike, laccolith, stock, or batholith passes upward into a lava flow. But a much more serious difficulty arises from imperfect exposures. This trouble is specially felt by students of the largest and most important of all intrusions, the so-called batholiths. It appears necessary to set them and their smaller

analogues, plutonic stocks and bosses, apart. Their definition, if objective and therefore acceptable, must to some extent be negative. Their mode of intrusion cannot be directly observed or directly inferred by the most careful field study. This fact should be emphasized in a genetic classification where batholithic masses enter but represent "unfinished business."

Most of the categories recognized in the geological literature refer to magmas essentially exotic. Each of those melts came into its chamber through one or more channels from larger bodies of melted rock at deep levels, generally not exposed by erosion. The chamber is due to the parting of the country rocks; hence a genetic feature in common for all members of a major group of intrusions—injected bodies. An **injected body** is thus one that is entirely inclosed by the invaded formations, except along the relatively narrow feeding channel.

In contrast are typical batholiths and plutonic stocks and bosses. These are not visibly floored; their emplacement is a problem much debated. They give no certain evidence of diminishing downward, as if their magmas had risen through narrow openings in the earth's crust. On the contrary, each typical body enlarges downward to some unknown limit. Thus, in relation to the invaded formations, batholiths, stocks, and bosses are intrusive but are here called **subjacent** rather than injected. This invention has the wholesome effect of stressing the mystery that still attaches to their style of emplacement and the need of further investigation concerning the mechanics of intrusion. It automatically aids thinking in a difficult field of research.[1]

If a downwardly enlarging intrusion, though in other respects resembling a batholith as here defined, can be proved to have a floor of country rock at the time of intrusion, that body should be placed in the group of injections. Examples abound in the early Pre-Cambrian terranes, where extensive granites, formerly called batholiths, have been shown to be of sheetlike, laccolithic, phacolithic, or lopolithic nature. Even some younger masses, long regarded as batholiths, are

[1] A number of geologists and petrologists, including Bowen, T. C. Chamberlin, R. T. Chamberlin, Erdmannsdorffer, Iddings, Lindgren, and others, are less conservative and believe that most, or all, batholiths, stocks, and bosses are floored injections in the sense just defined. Such a premature conclusion on one of the main questions of petrology is not supported by convincing evidence and, made by eminent leaders in geological circles, tends to discourage sound thinking among the younger workers in the field. The position of H. Cloos, whose able studies of the detailed structures and textures of many major salic intrusions are well-known, is not clear in this matter. In a systematic treatment of the "*Plutone*" (Fennia, vol. 50, 1928, pp. 4, 5) he states that he does not assume floors for batholiths but on the next page defines his "*Plutone*," which includes batholiths, as having visible or inferable floors (each with *einer etwa sichtbaren oder erschliessbaren Unterfläche*).

now described as of the injected class. Thus, according to Osman and also Brammall, the Dartmoor granite of England represents a triple "laccolith."[1]

The proposed classification follows:

A. Injected masses.
- I. Concordant injections (injected along planes of stratification or schistosity).
  1. Sills.
     - *a*. Simple: homogeneous and differentiated.
     - *b*. Multiple.
     - *c* Composite.
  2. Interformational sheets (at unconformities).
  3. Laccoliths.
     - *a*. Simple: symmetric and asymmetric, divided, homogeneous and differentiated.
     - *b*. Multiple.
     - *c*. Composite.
     - *d*. Interformational (at unconformities)
  4. Lopoliths (varieties analogous to those of laccoliths).
  5. Phacoliths.
  6. Ribbon injections.
- II. Discordant injections (injected across planes of stratification or schistosity).
  1. Dikes.
     - *a*. Simple: homogeneous and differentiated.
     - *b*. Multiple.
     - *c*. Composite.
  2. Dike swarms.
  3. Eruptive veins; contemporaneous veins.
  4. Apophyses or tongues.
  5. Ring dikes.
  6. Cone sheets.
  7. Volcanic necks.
  8. Bysmaliths.
  9. Ethmoliths.
  10. Sphenoliths.
  11. Akmoliths.
  12. Harpoliths.
  13. Sole injections.
  14. Chonoliths.

B. Subjacent masses.
- I. Batholiths.
  - *a*. Simple: homogeneous and differentiated.

[1] C. W. Osman, Quart. Jour. Geol. Soc. London, vol. 80, 1924, p. 335, and vol. 84, 1928, p. 261; A. Brammall, *ibid*., p. 336. Later (*ibid*., vol. 88, 1932, p. 172) Brammall stated that the evidence at Dartmoor is equivocal. *Cf*. J. W. Evans, *ibid*., vol. 82, 1926, p. lxxxviii, and F. H. Hatch and A. K. Wells, The Petrology of the Igneous Rocks, 8th ed., London, 1926, p. 509. According to H. C. Gunning (Trans. Roy. Soc. Canada, vol. 26 (*iv*), 1932, p. 300) the extensive Nimpkish granodiorite of Vancouver Island has a floor near the contact and he believes this fact to exclude the body from the class of batholiths. But does it? Many apophyses have floors but tell us little about the relations of their parent masses in depth.

b. Multiple.
c. Composite.

II. Stocks and bosses.
a. Simple: homogeneous and differentiated.
b. Multiple.
c. Composite.

An effort has been made to frame the classification so as to do least violence to the collective opinion of geologists and petrologists about the most useful phrasing of the definitions. Parts of the scheme will probably not win the approval of some of the author's colleagues, but it is hoped that it may promote clearness of understanding of the many chapters to come. The same may be said of the classification in Chapter VIII.[1]

CONCORDANT INJECTIONS

1. Sills are injections along planes of stratification or schistosity (rarely along independent, flat-lying master joints) and were emplaced when the invaded beds lay at low angles to the plane of the horizon (Figs. 1, 2). Most writers assume an active role for the sill magma, the roof being lifted from the floor by liquid pressure—the laccolithic mechanism.[2] To be considered is another—lopolithic—mode of intrusion, whereby the roof rocks remain steady and the space for the injected material is won by the sinking of the floor. The difficulty of distinguishing these two cases makes it advisable to refer both kinds of injections to the sill category. One might recognize the subclasses under the names "laccolithic sills" and "lopolithic sills."[3]

[1] More or less systematic classifications of intrusive bodies and associated topographic forms are to be found in the various textbooks of geology and in the more recent (German) handbooks of geophysics. Other general references to this broad subject include O. H. Erdmannsdörffer, Grundlagen der Petrographie, Stuttgart, 1924; A. Geikie, Ancient Volcanoes of Great Britain, London, 1897; F. F. Grout, Petrography and Petrology, New York, 1932; A. Harker, The Natural History of Igneous Rocks, New York, 1909; A. Holmes, The Nomenclature of Petrology, 2d ed., London, 1928 (invaluable for its careful and comprehensive handling of definitions); J. P. Iddings, Igneous Rocks, New York, 1909; G. Mercalli, I Vulcani Attivi della Terra, Milan, 1907; K. Sapper, Vulkankunde, Stuttgart, 1927; G. W. Tyrrell, The Principles of Petrology, London, 1926; F. von Wolff, Der Vulkanismus, Stuttgart, 1914.

[2] C. N. Fenner (Jour. Geol., vol. 33, 1925, p. 209, with references to papers by R. F. Griggs) thinks that the cubic mile of comminuted lava deposited in 1912 on the floor of the Valley of the Ten Thousand Smokes emanated from a sill, and that during the injection of this body at some moderate depth the valley floor was elevated temporarily about 65 meters above its present level. Griggs, however, regards the feeding mass as a batholith.

[3] F. Loewinson-Lessing describes the occurrence of a lopolithic sill in Siberia (Miner. u. Petrog. Mitt. Leipzig., vol. 43, 1932, p. 271).

Lenses or tabular masses injected along the bedding or schistosity of steeply dipping strata may be called "concordant sheets," or, if clearly emplaced by the dike mechanism, "concordant dikes."

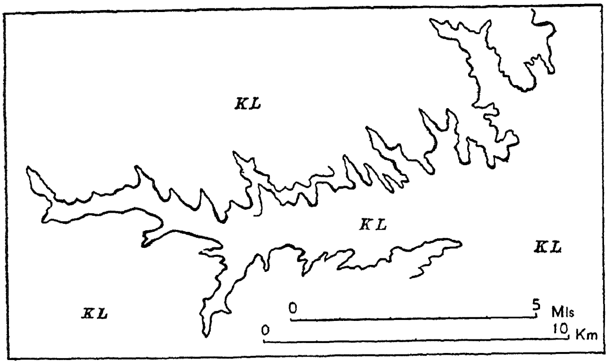

FIG. 1.—Outcrop of lamprophyric sill in flat Laramie sediments (*KL*), Colorado. (*After Spanish Peaks folio, U. S. Geol. Survey, No.* 71, 1901.)

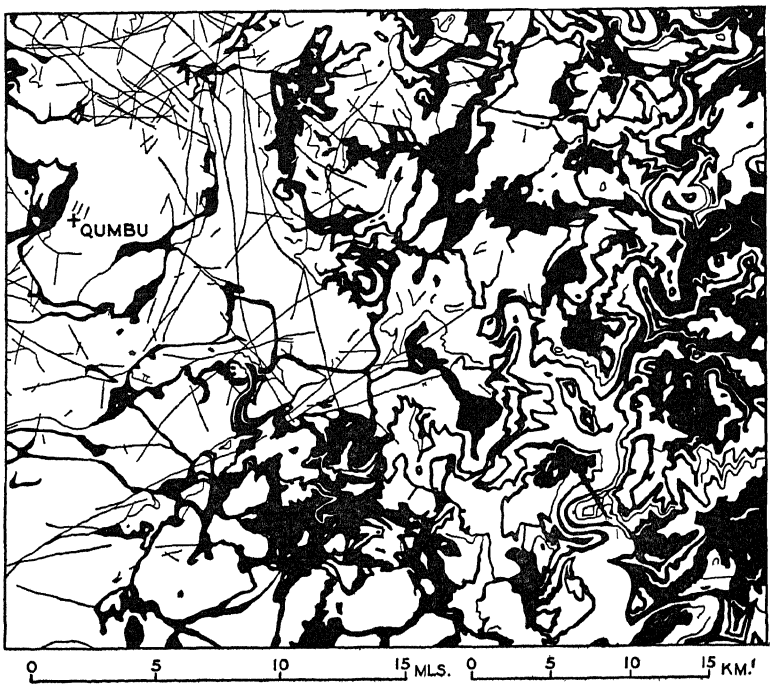

FIG. 2.—Map of complex of dolerite sheets (slightly crosscutting sills) in eastern part of Cape Province, South Africa. Sheets in *black;* Karroo sediments *left blank.* (*From areal map 27, by A. L. du Toit, Geol. Survey South Africa.*)

Magmatic changes after injection have characterized the subclass of **differentiated** sills (Fig. 143).

A **multiple sill** is the result of successive injections of one kind of magma along the appropriate structural plane in the country rock—apparently a rare case.

A **composite sill** is a compound intrusion of sill form and relations and is the result of successive injections of more than one kind of magma along a bedding plane (Fig. 3). Skye and Arran furnish good examples.[1] Another is figured in a paper on the coast geology of Greenland[2] (Fig. 184). According to Gilluly, a number of diabase-syenite composites cut the Mesozoic beds of the San Rafael Swell district, Utah.[3]

Sills vary in thickness from sheets of microscopic dimensions to those more than 600 meters in thickness. In all cases it is necessary that a sill shall hold its major thickness, at least approximately, for relatively great distances along its roof or floor.

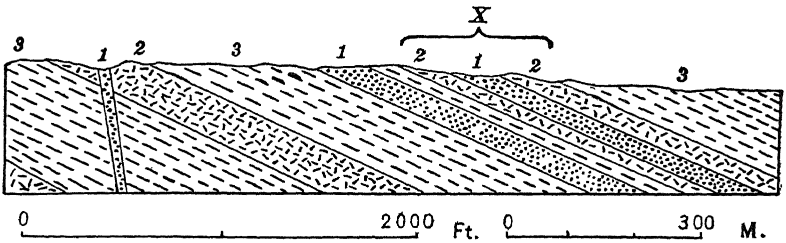

FIG. 3.—Simple and composite (*X*) sills cutting Tertiary strata at the Kettle River, British Columbia. *1*, rhomb-porphyry; *2*, pulaskite porphyry, cut by *1*; *3*, Oligocene sandstone and shale. (*R. A. Daly, Mem.* 38, *Geol. Survey Canada*, 1912, *Fig.* 25.)

Sills may be abundant in a single outcrop. The author has seen more than one hundred sills at a cliff section, 800 meters high, in the Pre-Cambrian sediments (Shuswap series) of the Columbia Mountain range, British Columbia, and has counted twenty-five sills in a 10-meter cliff section of the same terrane. The sills of the Purcell Range, Idaho and British Columbia, are as notable for their number as for great individual thicknesses. (Figs. 4 and 143.) The post-Cobalt sills of Ontario represent another Canadian assemblage of importance.[4]

The greatest of the Triassic sills of New Jersey reaches 300 meters in thickness and has about 160 kilometers of residual length of outcrop (Fig. 185). The famous Whin Sill has a maximum known thickness of but 50 meters (average thickness 25 to 30 meters), but the length of its mapped outcrop is more than 130 kilometers and its underground

[1] A. Harker, Tertiary Igneous Rocks of Skye, Memoir Geol. Survey Scotland, 1904, pp. 204 and 257. G. W. Tyrrell, Arran memoir, Geol. Survey Scotland, 1928, pp. 115, 123 *ff*.

[2] A. Heim, Medd. om Grönland, vol. 47, 1911, p. 203.

[3] J. Gilluly, Amer. Jour. Science, vol. 14, 1927, p. 200.

[4] *Cf.* W. H. Collins, Mem. 95, Geol. Survey Canada, 1917, pp. 84 *ff*.

spread nearly 4000 square kilometers (G. W. Tyrrell). The Cape Province, South Africa, is rich in extended intrusions of this class (sill swarms, Fig. 2). The lowest of the dolerite sills of Calvinia is continuous over at least 7600 square kilometers, and one near Hopetown covers more than 13,000 square kilometers. Another dolerite

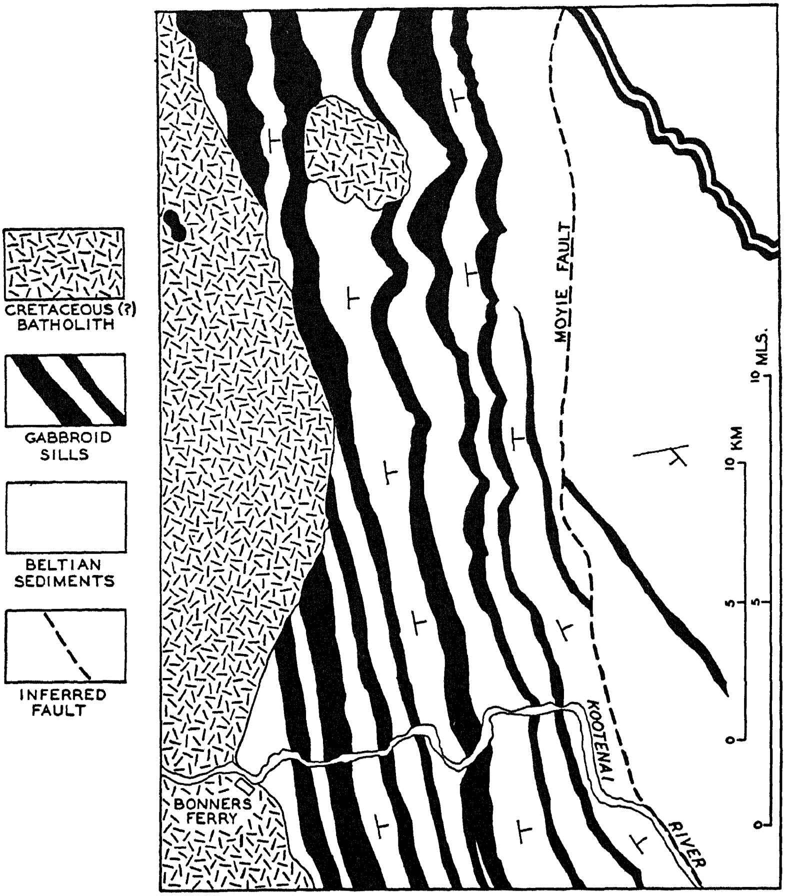

Fig. 4.—Map of thick gabbro sills cutting Beltian (late Pre-Cambrian) strata in Idaho; all invaded by younger "Nelson" batholith. See also Fig. 43. (*After V. R. D. Kirkham and E. W. Ellis, Bull.* 10, *Idaho Bur. of Mines*, 1926.)

sheet between Langebergen and Tanqua Valley, though reaching a maximum known thickness of only 90 meters, has an outcrop 160 kilometers long. The Rooi Hoogte sheet fronts the Great Karroo for nearly 80 kilometers and has an outcrop more than 110 kilometers in length.[1] "Immense" sills and dikes cut the Archean, Cambrian

[1] A. W. Rogers and A. L. du Toit, Geology of Cape Colony, London, 2d ed., 1909, pp. 261–264; Ann. Rep. Geol. Comm. Cape of Good Hope, 1903, pp. 37–39.

limestone, and Beacon sandstone of Antarctica through a coastal stretch of 750 kilometers.[1]

Such statistics make it easier to believe that the colossal eruptions of gabbroid and noritic magmas in Minnesota (Duluth), South Africa (Bushveld), Sierra Leone, etc., had solid floors more extensive than the respective fractions actually visible or even directly inferred from direct observation.

Sills vary greatly in composition, from peridotite to highly siliceous aplites. The Archean complexes carry countless granitic sills, some of wide extension and considerable thickness. The most imposing examples of Paleozoic and later dates of intrusion are almost exclusively basic—diabasic, gabbroid, or noritic.

2. Closely related is a tabular body, intruded along a plane of unconformity and parallel to the bedding of one of the invaded formations. Such intrusions may be called **interformational sheets.** A classic example is that in the Sudbury district of Ontario (Fig. 146).[2] Though perhaps begun at greater depth, the differentiation of the Sudbury magma was completed after injection at the visible horizon.

3. Those who have made actual researches among **laccoliths,** and have adopted Gilbert's original definition, are agreed on the following characteristics: (*a*) Whatever the origin of the force involved, each laccolith was injected. (*b*) Like a sill, a typical laccolith has followed a bedding plane, though locally it may have broken its way across the bedding. (*c*) A laccolith has the shape of a planoconvex or doubly convex lens, flattened in the plane of bedding of the invaded formation. The lens may be symmetrical or asymmetrical in profile; circular, elliptical, or irregular in ground plan. (*d*) There are all transitions between sills and laccoliths. (*e*) A laccolith lifted its roof during injection.[3]

A number of special students of laccoliths hold that the emplacement of at least some of them was essentially facilitated by antecedent or simultaneous upward buckling of the roof sediments under tangential crust pressure—a mechanical condition not included in Gilbert's definition.[4] Among the examples are, according to Gould, those of the

[1] H. T. Ferrar, quoted by R. E. Priestley and T. W. E. David in Compte Rendu, Cong. Géol. Internat., 11th session, Stockholm, 1910, p. 784.

[2] A. E. Barlow, Ann. Rep. Geol. Survey Canada, vol. 14, part H, 1904. A. P. Coleman, Rep. Bur. Mines, Ontario, vol. 14, part 3, 1905.

[3] G. K. Gilbert, Report on the Geology of the Henry Mountains, Washington, 1877, pp. 20, 55, 91, 95.

[4] W. Cross, 14th Ann. Rep. U.S. Geol. Survey, part 2, 1894, p. 236. T. A. Jaggar, 21st Ann. Rep. U.S. Geol. Survey, part 3, 1901, p. 290. E. Kaiser, Neues Jahrb. f. Mineralogie, etc., B.B. 39, 1914, p. 262. C. R. Keyes, Bull. Geol. Soc. America, vol. 29, 1918, p. 75. W. H. Hobbs, Earth Evolution and Its Facial

La Sal Mountains, Utah. One reason for his there assuming a major control by the stresses of folding is the elongation of these particular "laccoliths." A useful bibliography of the subject will be found in Gould's paper.

This extension of "laccolith" beyond Gilbert's definition, so as to cover genetically different things, is hardly qualified to add to clearness of geological and petrological thought, for there can be little doubt that the Gilbert mechanism is actually illustrated by many of these injected lenses. Those emplaced with the essential aid of tangential compression in the surrounding crust can be called phacoliths (see below) without unduly straining Harker's definition of this term.[1]

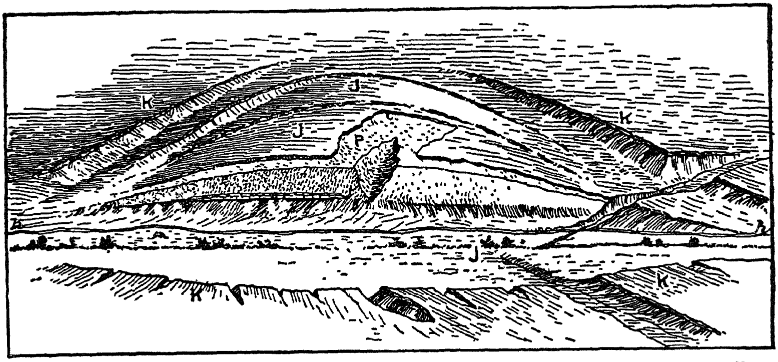

FIG. 5.—Stereographic sketch of the Warm Spring laccolith, Montana. *P*, porphyry of laccolith, dotted; *K*, Cretaceous strata; *J*, Jurassic strata; *h*, road. (*W. H. Weed and L. V. Pirsson, 18th Ann. Rep., U. S. Geol. Survey, part* 3, 1898, *p.* 519.)

Illustrations of **simple** laccoliths are given in Figs. 5, 6, and 7. The Tenmile district special folio of the United States Geological Survey represents laccoliths in abundance and as well examples of transitions to sills.

Paige has published a suggestive study of the relation of the form of a laccolith to the increase of magmatic cooling and resulting heightened viscosity along the margins. Under certain conditions the viscosity may become so great as to cause the igneous material to break sharply across the roof and develop centrally the structural relations of a bysmalith (Fig. 8).[2]

A **multiple laccolith** is the result of distinctly successive injections of the same kind of magma. Harker ascribes this character to the gabbro laccolith of the Cuillin Hills, Island of Skye. As already noted,

Expression, New York, 1921, p. 54. R. Staub, Schweiz. Min. u. Petr. Mitt., vol. 2, 1922, p. 143. L. M. Gould, Amer. Jour. Science, vol. 12, 1926, p. 119.

[1] *Cf.* A. Harker, The Natural History of Igneous Rocks, New York, 1909, p. 65.

[2] S. Paige, Jour. Geol., vol. 21, 1913, p. 547. See an account of relevant experiments by G. R. MacCarthy, *ibid.*, vol. 33, 1925, p. 1.

Osman believes the Dartmoor granite to be a triple laccolith, though he uses "laccolith" in a sense different from that of Gilbert.[1]

On the other hand, **composite laccoliths** are made up of two or more kinds of magma, successively intruded. This type is illustrated by

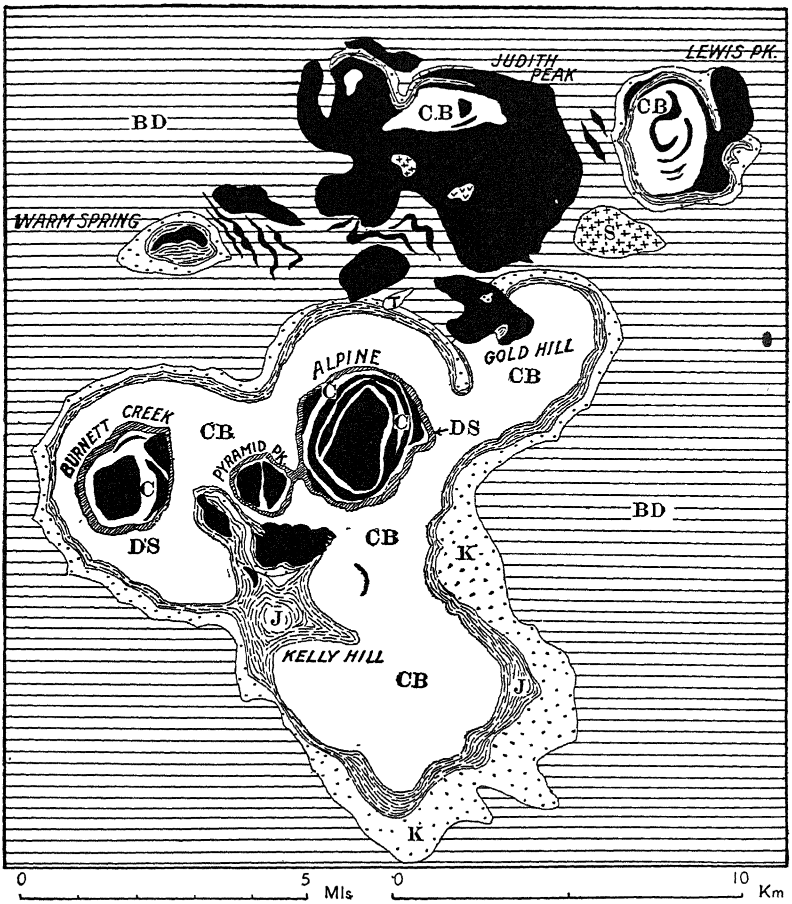

FIG. 6.—Laccoliths of the Judith Mountains, Montana. *Solid black*, acidic porphyries of the laccoliths; *inverted carets*, granite porphyry, *S*, syenite; *T*, tinguaite; *BD*, Benton and Dakota shales and sandstones; *K*, Kootanie shales and sandstones; *J*, Jurassic shales and limestones; *CB*, Carboniferous limestone; *DS*, Devonian and Silurian limestones; *C*, Cambrian shales and limestones. (*After W. H. Weed and L. V. Pirsson*, *18th Ann. Rep.*, *U. S. Geol. Survey*, *part* 3, 1898, *Plate* 75.)

Fig. 9 and again by the alkaline mass of Loch Alsh.[2] A more complicated case is the double laccolith of Lake Dufault, Quebec, each

[1] A. Harker, Tertiary Igneous Rocks of Skye, Glasgow, 1904, p. 88.

[2] J. Phemister, The Geology of Strath Oykell, etc., Memoir Geol. Survey Scotland, 1926, p. 83.

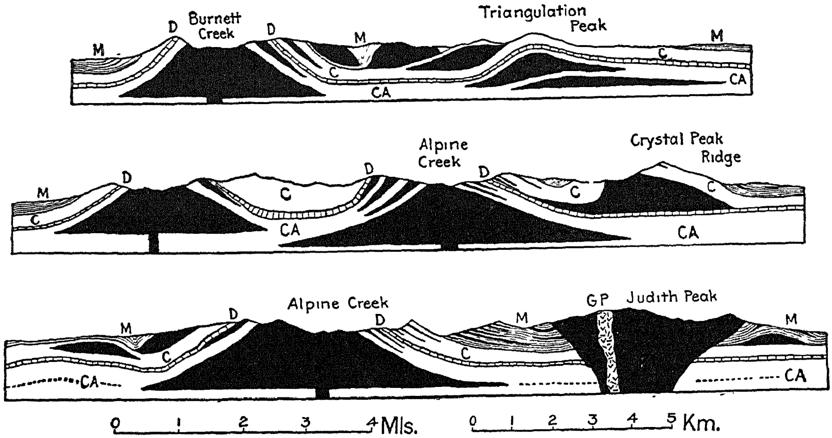

FIG. 7.—Sections of area shown in Fig. 6. *Solid black*, acidic porphyries of the laccoliths; *GP*, granite porphyry; *M*, Mesozoic shales, limestones, etc.; *C*, massive Carboniferous limestone; *D*, Devonian limestone; *CA*, Cambrian shales and thin-bedded limestones.

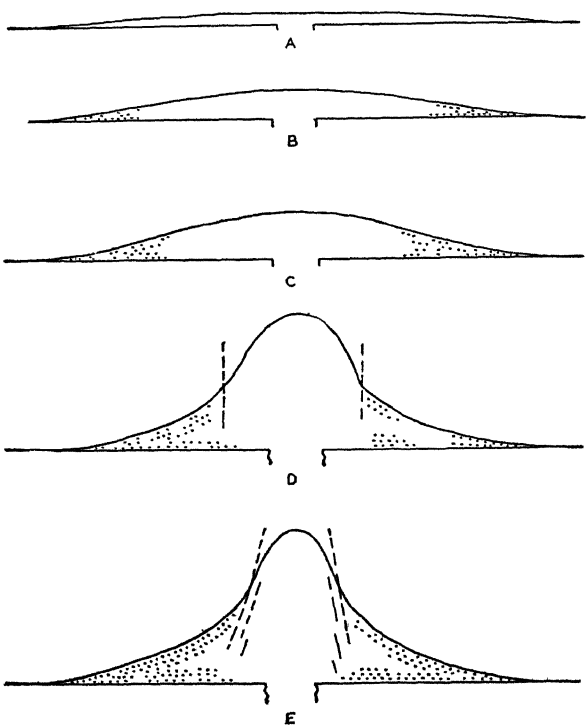

FIG. 8.—Serial diagram illustrating the effect of marginal cooling and increasing viscosity on the shape of a laccolith. Progression from *A* to *E*. (*S. Paige, Jour. Geol., vol.* 21, 1913, *p.* 547.)

component of which was gravitatively differentiated to give various dioritic and granitic phases (see No. 5 in Table 40).[1]

A class of "compound laccoliths" was recognized by Weed and Pirsson in the Judith Mountains, Montana. These, like some of the larger Henry Mountains laccoliths, are divided by beds of the invaded

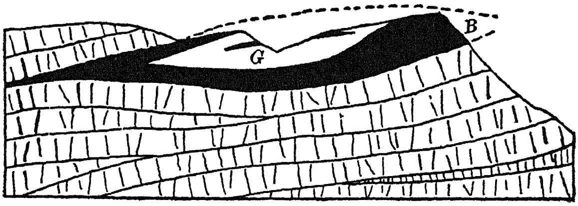

Fig. 9.—Section of a composite laccolith in Skye. *B*, basalt; *G*, granophyre. The granophyre pod cuts the intrusive basalt which is itself intrusive into basaltic lavas. The maximum thickness of the laccolith is 45 meters. (*After A. Harker, Tertiary Igneous Rocks of Skye, Glasgow*, 1904, *p.* 209.)

formations, though at each locality the whole magma appears to have been emplaced by a single act of intrusion. Students find difficulty in remembering the distinctions among "compound," "multiple," and "composite" laccoliths. Hence it may be suggested that the

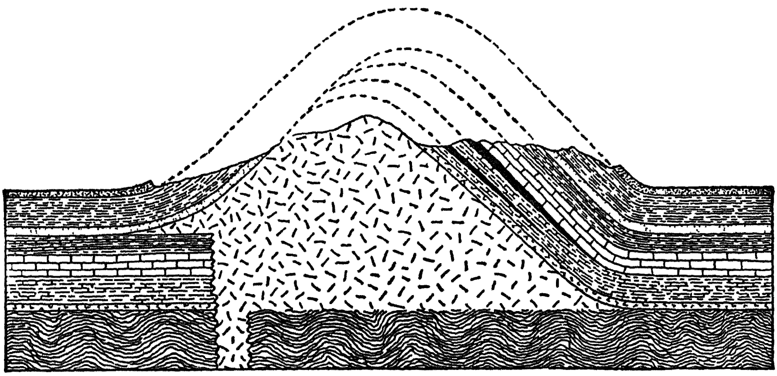

Fig. 10.—Section of asymmetric interformational laccolith at Black Butte, Montana. (*Same reference as for Fig. 5, loc. cit., p.* 555.)

rare bodies of this Judith Mountain type be described as **divided** simple laccoliths.

Corresponding to interformational sheets are **interformational laccoliths.** Examples have been found by Weed and Pirsson, Irving, and Darton (Figs. 10 and 11).[2]

[1] H. C. Cooke, Trans. Roy. Soc. Canada, vol. 24 (*iv*), 1930, p. 89.

[2] W. H. Weed and L. V. Pirsson, 18th Ann. Rep., U.S. Geol. Survey, part 3, 1898, p. 580; Jour. Geol., vol. 4, 1896, p. 402. J. D. Irving, Annals New York Acad. Sciences, vol. 12, 1899, p. 206. N. H. Darton, Sundance folio, U.S. Geol. Survey.

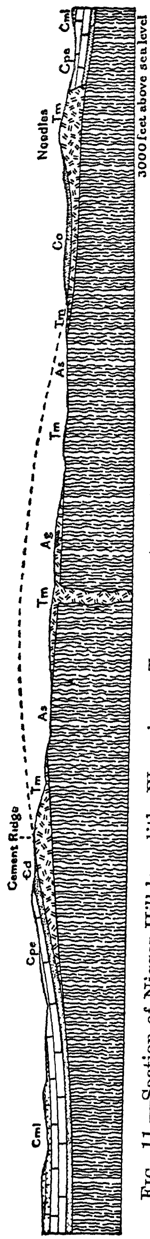

FIG. 11.—Section of Nigger Hill laccolith, Wyoming. *Tm*, monzonite and syenite porphyries, *Cml*, Minnelusa sandstone; *Cpe*, Pahasapa and Englewood limestones; *Cd*, Cambrian sandstone; *Ag*, granite and pegmatite; *As*, mica schist. Horizontal and vertical scales, about 1·86,000. (*Sundance folio, U. S. Geol. Survey,* 1905.)

Seldom are the feeding channels of laccoliths exposed. Geologists who have mapped these bodies agree in postulating narrow channels, actually dikes or of dikelike width.

A few laccoliths are considered to have broken through their roofs and to have reached the earth's surface through openings much wider than that of an ordinary dike or volcanic vent. These are the *Eruptionslakkolithe* of Erdmannsdörffer. Stark has described an example in the Euganean Hills. Another was discovered by Robinson in the San Francisco Mountains of Arizona (Fig. 62).[1]

Laccoliths have a wide range of chemical composition. Cross made a canvass of the laccoliths of Colorado, Utah, and Arizona.[2] His list of the petrographic types includes augite porphyrite, hornblende porphyrite, porphyritic augite diorite, quartz porphyrite, and quartz porphyry. Some of these species would now, probably, be called monzonite porphyries. In the Highwood Mountains of Montana the rocks forming laccoliths include sodalite syenite, shonkinite, basic syenite, and leucite-basalt porphyry.[3] Granite porphyry, rhyolite porphyry, syenite porphyry, and diorite porphyrite compose the many laccoliths of the Judith Mountains, Montana.[4]

The types represented in the laccoliths of the Black Hills, South Dakota, include grorudite, phonolite, rhyolite porphyry, dacite, andesite porphyry, syenite porphyry, and diorite porphyrite.[5] Hills describes laccoliths of doleritic rock, found in Huerfano Park, Colorado.[6] Gabbro laccoliths are reported from the island of Skye, and they seem to have been developed on a large scale in the area

[1] H. H. Robinson, Prof. Paper 76, U.S. Geol Survey, 1913, p. 83.

[2] W. Cross, 14th Ann. Rep. U.S. Geol. Survey, part 2, 1894, p. 165.

[3] L. V. Pirsson, Bull. 237, U.S. Geol. Survey, 1905, pp. 57 *ff*.

[4] W. H. Weed and L. V. Pirsson, 18th Ann. Rep., U.S. Geol. Survey, part 3, 1898, pp. 557 *ff*.

[5] T. A. Jaggar, Jr., 21st Ann. Rep., U.S. Geol. Survey, part 3, 1901, p. 182.

[6] R. C. Hills, Proc. Colorado Scientific Soc., vol. 3, part 2, 1889, p. 226.

covered by the Roseburg folio of the United States Geological Survey, as well as in Minnesota and other states of the Union. At least ten of the laccoliths underlying the thirty-two domes of the Runn of Cutch are composed of quartz-bearing diabase.[1] Theralite forms laccoliths of the Crazy Mountains, Montana. Ijolite, urtite, and nephelite syenite constitute the supposed laccolith of the Kola Peninsula.

Without further multiplying examples, it is clear that all, or nearly all, the igneous clans are represented among the laccolithic injections.

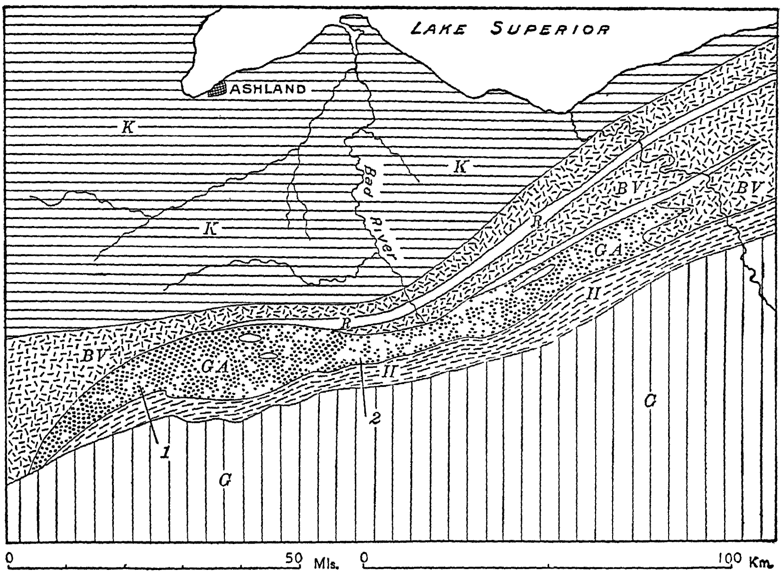

FIG. 12.—Map of what appears to be the southern outcrop of the Duluth gabbro lopolith (see F. F. Grout, Amer. Jour. Science, vol. 46, 1918, pp. 518, 521). *G*, pre-Huronian schists, granite, etc.; *H*, Animikie slates, quartzites, etc.; *BV*, Keweenawan basic volcanics; *GA*, gabbro lopolith; *R*, "red rock" (granite, etc.). Sections at *1* and *2* are given in "Igneous Rocks and Their Origin" (p. 329).

4. According to Grout, the inventor of the term, "a **lopolith** may be defined as a large, lenticular, centrally sunken, generally concordant, intrusive mass, with its thickness approximately one-tenth to one-twentieth of its width or diameter." Grout recognized "varying degrees of complexity described as 'multiple,' 'composite,' 'divided,' 'interformational,' as distinguished from 'simple.'" The Duluth gabbro, "a multiple, composite, divided lopolith" with an estimated volume of 200,000 cubic kilometers, is the type (Figs. 12 and 139).[2] The analogous, much larger norite-granite-granophyre-felsite body of the Bushveld Complex as a whole is not strictly a lopolith, because its

[1] J. F. Blake, Quart. Jour. Geol. Soc., vol. 54, 1898, p. 12.
[2] F. F. Grout, Amer. Jour. Science, vol. 46, 1918, p. 518.

composite magma seems to have had no continuous roof other than its own chilled phase and was thus in a sense effusive. On the other hand, the great noritic part of it, intrusive into the slightly older effusive part, may fairly be classed with the lopoliths (Fig. 90). The intrusion of the basic magmas of both the Duluth and Bushveld lopoliths appears to have been accompanied and facilitated by the sinking of their respective floors, each floor subsidence being at maximum in the central part. The Sudbury norite-micropegmatite body (Fig. 146) may be a third example, though it is here possible that the

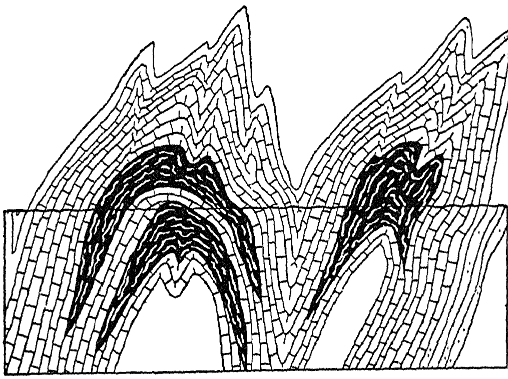

FIG. 13.—Section of Gouverneur and Reservoir Hill phacoliths, New York State, with reconstruction above the existing erosion surface. White lines on the black of the granitic phacoliths represent foliation. (*A. F. Buddington, Bull.* 281, *New York State Museum*, 1929, *p.* 56.)

basining was caused chiefly by tangential orogenic pressure after or during intrusion. The multiple laccolith of the Cuillin Hills, Skye, and also the "batholith" of Ilimausak, Greenland, exhibit centripetal dips of their respective floors and are probably best described as lopoliths.[1]

These cases suggest that, when magma is transferred on a large scale into a floored chamber or surface of great horizontal extent, such floor or surface sinks and sinks most in the central part. The principle is illustrated further where thick and widespread plateau basalts have been erupted.

5. Harker has introduced the name *phacolite* (here **phacolith,** meaning literally "lens rock") for a fourth class of concordant injections. His description may be quoted.

In the ideal case of a system of undulatory folds there is increased pressure and compression in the middle limbs of the folds, but in the crests and troughs a relief of pressure and a certain tendency to opening of the bedding-surfaces.

[1] A. Harker, Tertiary Igneous Rocks of Skye, 1904, pp. 85, 423; N. V. Ussing, Medd. om Grönland, vol. 38, 1911, p. 322.

A concurrent influx of molten magma will therefore find its way along the crests and troughs of the wave-like folds. Intrusive bodies corresponding more or less closely with this ideal case are common in folded districts. Since some distinctive name seems to be needed, we may call them *phacolites*. The name laccolite has often been extended to include such bodies, but this is to confuse together two things radically different. The intrusions now considered are not, like true laccolites, the cause of the attendant folding, but rather a consequence of it. The situation, habit, magnitude, and form of the phacolite are all determined by the circumstances of the folding itself. In cross-section it has not the plano-convex shape of the laccolite but presents typically a meniscus, or sometimes a doubly convex form. Except where the

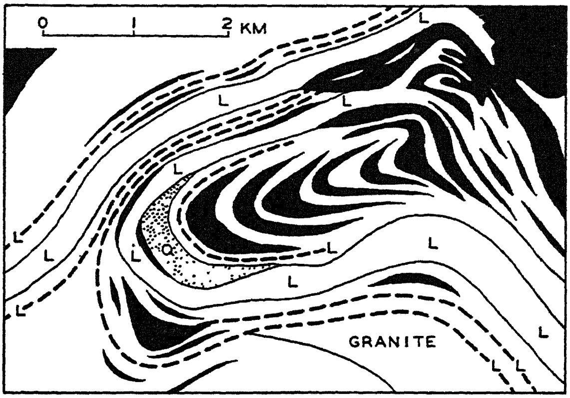

FIG. 14.—Map of Pre-Cambrian phacoliths and associated concordant injections of granite (*solid black*, with one large area left *blank* but marked as granite), cutting a thick sedimentary series of mica schists (*blank*), marbles (*L*), and quartzite (*Q*). (*After T. W. Gevers and H. F. Frommurze, Trans. Geol. Soc. South Africa, vol.* 32, 1929, *p.* 51.)

folding has the character of a dome, a phacolite does not show the nearly circular ground-plan of a laccolite, but has a long diameter in the direction of the axes of folding. As regards the mechanical conditions of its injection, the phacolite resembles rather the small subsidiary intrusions which sometimes accompany a laccolite, and are consequences of the sharp flexure caused by the primary intrusion.[1]

Kaiser now regards the large intrusion at Monchique, Portugal, as another example. According to Buddington, numerous phacoliths are to be found among the extensive Pre-Cambrian granites of New York State (Fig. 13) and eastern Canada[2] (compare Fig. 14).

6. The name **ribbon injection** has been given to long, thin, narrow apophyses of red rock from the differentiated sill at Pigeon Point,

[1] A. Harker, The Natural History of Igneous Rocks, New York, 1909, p. 78.

[2] E. Kaiser, Sitzungsber. Bayer. Akad. Wiss., math.-phys. Kl., 1922, p. 256. A. F. Buddington, Bull. 281, New York State Museum, 1929, p. 51. *Cf.* T. Quirke, Jour. Geol., vol. 37, 1929, p. 683.

Minnesota (Fig. 15). The ribbons are in general like flat nails driven into the metargillitic country rock, with the flat side of the nail in the plane of bedding. Laterally the "nails" sharply truncate the bedding. The maximum length observed was several meters; the maximum widths and thicknesses are measurable in millimeters. How the country rock yielded so as to permit these small magmatic bodies to

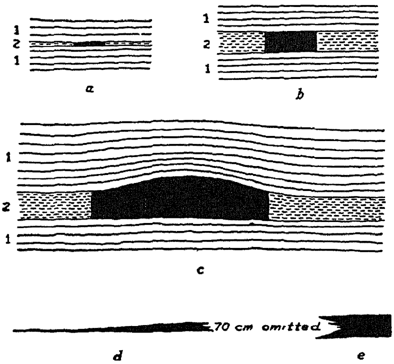

FIG. 15.—Cross sections (*a*, *b*, and *c*) and partial ground plan (*d*, *e*) of ribbon injections of red rock (*dotted*), cutting across metargillitic layers (2) between beds of micaceous quartzite (1). All drawings on about two-thirds of natural scale. (*R. A. Daly, Amer. Jour. Science, vol.* 43, 1917, *p.* 432.)

have their clean-cut rectangular cross sections is an intriguing problem; its solution may possibly have some importance in a general explanation of magmatic injection.[1]

DISCORDANT INJECTIONS

1. By a commonly held definition a **simple dike** (*a*) is an injected body, (*b*) has nearly or quite parallel walls, (*c*) is narrow in proportion to its outcropping edge, (*d*) in most instances cuts across the bedding when the invaded formation is stratified, and (*e*) has any angle of dip. Evidently some dikes with low dips are hard to distinguish from sills moderately transgressive among flat-lying sediments.

Where the stratification and cleavage or schistosity of the country rock are not coincident in dip, the injected body is generally called a "dike," even though it follows one or other of the secondary structures. An initially flat-lying sheet injected into massive rocks like granite was probably emplaced by the sill mechanism, but, if it be desirable to retain the prevailing textbook definition of "sill," such a body might be called simply an intrusive sheet.[2]

[1] See R. A. Daly, Amer. Jour. Science, vol. 43, 1917, p. 431.

[2] For illustrations see B. Lightfoot and R. Tyndale-Biscoe, Bull. 10, Geol. Survey Rhodesia, 1931, p. 41, and map with section; also R. A. Daly in W. T. Grenfell and others, Labrador, New York, 1909, p. 98.

Supposed examples of **differentiated dikes** have been mapped in Thuringia. However, these and other narrow dikes, showing strong chemical difference between wall and middle, may prove to be of the composite class.

Multiple dikes are intrusions of dike form, due to successive injections of one kind of magma into the same, intermittently widened fissure

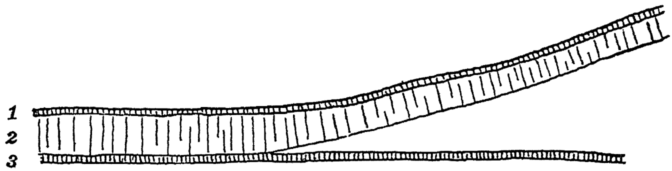

FIG 16.—Multiple (triple) basaltic dike cutting granophyre, St. Kilda Island. *1*, *2*, and *3*, separate intrusions. (*After A. Geikie, Ancient Volcanoes of Great Britain, vol. 2, London,* 1897, *p.* 417.)

(Fig. 16). They are much more numerous than either multiple sills or multiple laccoliths. A remarkable example is that in the eastern part of St. Helena Island. "On the razor-back ridge connecting The Barn with Flagstaff Hill is the outcrop of a multiple dike, which is made up of nearly 200 single dikes, between which no tuff or other different material could be found."[1] The individual dike members

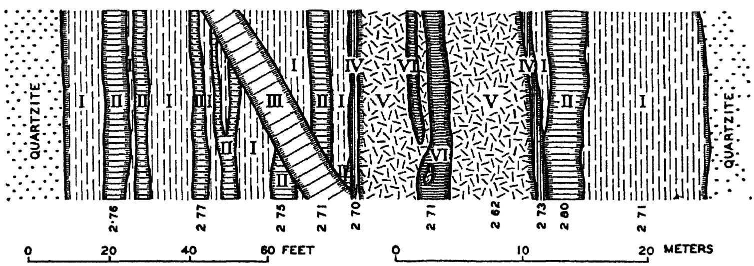

FIG. 17.—Map of composite dike, Glen Etive, Scotland. In order of injection: *I*, porphyrite; *II–IV*, malchites; *V*, quartz porphyry, *VI*, malchitic porphyrite. Densities of the various rocks are entered. (*After H. B. Maufe, The Geology of Ben Nevis, etc., Memoir Geol. Survey Scotland,* 1916, *p.* 145.)

regularly showed contact chilling and were identified with comparative ease; all seemed to be basaltic.

Composite dikes were formed by successive injections of chemically differing melts into the same fissure which widens to receive them (Fig. 17). An interesting example in eastern Iceland is ably discussed by Guppy and Hawkes[2] (Fig. 18). According to Krokström, the great Brefven (Breven) dike of Sweden falls in the composite class, the

[1] R. A. Daly, Proc. Amer. Acad. Arts and Sciences, vol. 62, 1927, p. 57.

[2] E. M. Guppy and L. Hawkes, Quart. Jour. Geol. Soc. London, vol. 81, 1925, p. 325.

successive intrusions being olivine dolerite, olivine-free dolerite, granophyre, and olivine dolerite. Winge's older map of this body (Fig. 19) illustrates the general distribution of the acid and basic rocks.[1]

Harker's "Natural History of the Igneous Rocks" contains a useful set of diagrams illustrating irregularities in the forms of dikes.

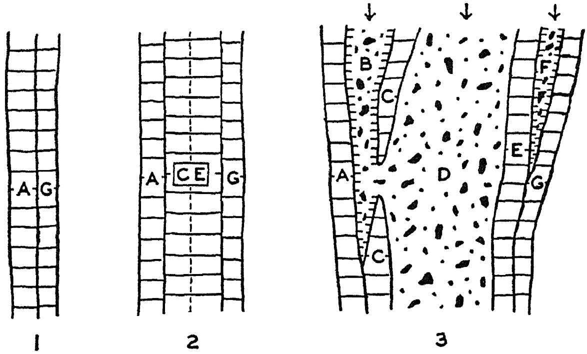

FIG. 18.—Stages in the development of an Icelandic composite dike. In order of injection: *AG*, dolerite; *BF*, quartz porphyry, in middle of *AG*; *CE*, dolerite, in middle of *BF*; *D*, quartz porphyry, in middle of *CE*. Width of dike at top (Stage 3) is 26 meters. (*After E. M. Guppy and L. Hawkes, Quart. Jour. Geol. Soc. London, vol.* 81, 1925, *p.* 337.)

No lower limit can be safely assigned to the possible width of a dike. A glassy (diabase) dike in Pelham, Massachusetts, only 0.9 millimeter wide, has apophyses ranging from 0.5 to 0.02 millimeter in

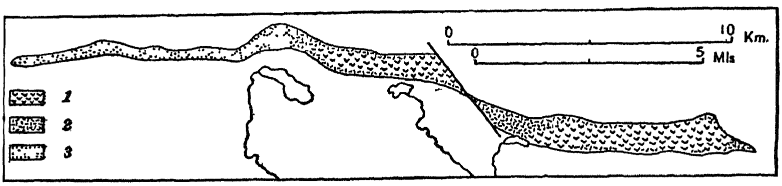

FIG. 19.—Plan of the dike at Brefven (Breven), Sweden. *1*, granite porphyry; *2*, intermediate rock; *3*, olivine diabase. (*After K. Winge.*)

width. A tachylitic dike cutting the gneiss of the same district is 2 millimeters wide, with apophyses about 0.1 millimeter wide.[2] A sharp line can not be drawn between true dikes and mineral veins deposited by water or other volatile fluids, which are capable of search-

[1] T. Krokström, Bull. Geol. Inst. Univ. Upsala, vol. 23, 1932, p. 243; K. Winge, Geol. Foren. Förh. Stockholm, vol. 18, 1896, p. 187. Krokström does not distinguish on his map more than two phases (granophyre, corresponding to the "granite porphyry" of Winge; and more basic rock, including the "intermediate rock" of Winge). Krokström speculatively concludes that all four types of magma actually broke through to the earth's surface and had effusive phases, nearly all of which have been completely removed by erosion.

[2] B. K. Emerson, Mon. 29, U.S. Geol. Survey, 1898, p. 416.

ing out the minutest crevice. Yet multitudes of basic dikes that give no indication of having been specially charged with gas have great lengths and small widths. Such dimensions imply low magmatic viscosity and also rapidity of injection.[1]

It is important to note that the lengths of many dikes are of the same order as those of the largest batholiths yet mapped. Two

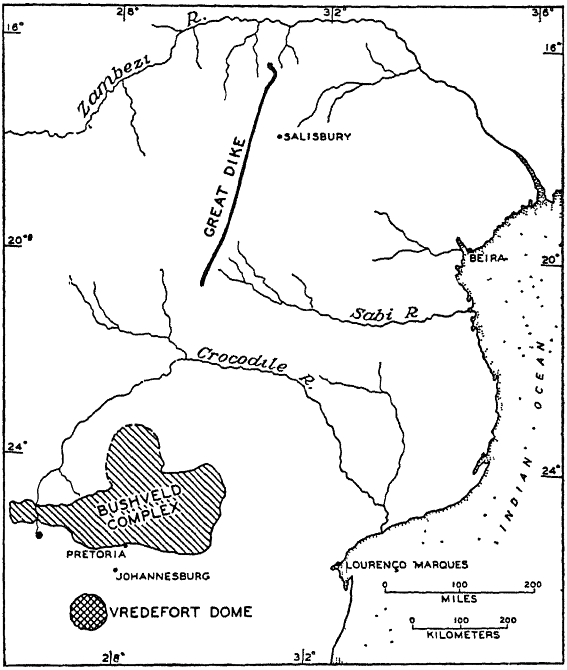

FIG. 20.—Sketch map of the Great Dike of Rhodesia, showing its geographical relation to the Bushveld Igneous Complex and to the Vredefort dome. (*Sketch based on geological map in A. L. du Toit, The Geology of South Africa, Edinburgh,* 1926.)

diabase dikes of northern Maryland are, respectively, 61 and 72 kilometers long at their outcrops.[2] One of Deccan Trap age in India is 64 kilometers in length.[3] A dolerite dike in Matatiele, Cape Province, is 24 kilometers long and up to 1600 meters wide. Another, running through Beukes Fontein, is 21 kilometers long and about 30 meters wide. A third dike, over 70 kilometers long, runs between Mt. Fletcher and Mt. Frere in the Drakensberg region.[4]

[1] *Cf.* J. Barrell, Prof. Paper 57, U.S. Geol. Survey, 1907, p. 157.

[2] Maryland Geological Survey, vol. 6, 1906, map.

[3] Cyril Fox, Rec. Geol. Survey India, vol. 44, part 2, 1914, p. 135.

[4] A. W. Rogers and A. L. du Toit, Geology of Cape Colony, 2d ed., London, 1909, pp. 231, 260. A. L. du Toit, 15th Ann. Rep. Geol. Comm. Cape of Good Hope, 1910, p. 99.

The so-called Great Dike of Rhodesia is one of the wonders of geology. Composed of basic and ultrabasic rocks, it measures 500 kilometers in length by 3 to 12 kilometers in width (Fig. 20). Its magma was differentiated into a series of long lenses of contrasted rocks, the lenses dipping gently toward the middle of the body. This type of banding, quite unusual in dikes, together with the discovery of country rock (granite) locally underlying the basic mass, led Wagner to suggest that the body is a greatly elongated sill. For the same reasons Lightfoot asks whether we have here to do with a gigantic ribbon injection, injected from the northern end or from vents along the course of the "dike." On the other hand, Shand thinks that the observed layering is quite possible in a true dike. It is noteworthy that the colossus is paralleled for long distances by basic injections of such form and relations as to permit little doubt of their being dikes. Thus the name "Great Dike" for the larger body seems not to lack some justification through analogy.[1]

The Cleveland dike of northern England is at least 175 kilometers long and, according to Geikie, may be as long as 300 kilometers. Scottish dikes with respective lengths of 40, 48, 58, 75, 80, 93, and 96 kilometers are recorded. Thoroddsen found the basaltic dikes of Iceland to reach lengths up to 105 kilometers.[2]

2. A system of many dikes that run more or less parallel or else radiate out from a center may be called, following the Scottish geologists, a **dike swarm.** Typical examples appear in the Western Isles of Scotland as well as on the mainland of that country (Figs. 21 and 117). Other illustrations are those of the Spanish Peaks region of Colorado (Fig. 22), Corsica, and Southwest Africa.[3] Dike swarms

[1] P. A. Wagner, Trans. Geol. Soc South Africa, vol. 17, 1914, p. 51 S J. Shand, *ibid.*, vol. 31, 1928, p. 151. See also the important papers on parts of the Great Dike by F. P. Mennell and A. Frost (Proc. Rhodesia Sci. Assoc., vol. 25, 1926, p. 1); by B. Lightfoot (Short Rep. 21, Geol. Survey Southern Rhodesia, 1927); and by F. E. Keep (Bull. 12 of the same Survey, 1929, p. 69, and Bull. 16, 1930, p. 48). A. L. du Toit (The Geology of South Africa, 1926, p. 151) gives references to the relevant writings of Mennell and Zealley, and also a lithographed map showing the alinement of the Great Dike with the Bushveld Igneous Complex and the Vredefort Dome, two other unique features of marvelous South Africa.

Is the Great Dike possibly the erosion-remnant of a taphrolith? (See page 141.) When we have sufficient data about the contact relations, it seems likely that light will be thrown on the mode of eruption of the Bushveld Complex, which in lithology and differentiation shows so much similarity to the Great Dike.

[2] A. Geikie, Ancient Volcanoes of Great Britain, London, vol. 2, 1897, p. 143. T. Thoroddsen, Petermann's Mitt., Erg. Heft 152, 1905, p. 250.

[3] For graphic maps of the African cases see E. Kaiser (Die Diamantenwüste Südwest-Afrikas, Berlin, 1926, Tafel C) and H. Cloos (Neues Jahrb. f. Mineralogie, etc., B.B. 66 (B), Heft 1, 1930, Tafel 3).

are specially conspicuous in eroded areas of former fissure eruption, as in the State of Washington (Fig. 57), Mull, and Arran.

3. Intrusive veins were defined by Jukes as follows:

When the injected mass has arisen along an opened fissure, and solidified there as a wall-like intrusion, it is called a *dyke*. When its path has been less

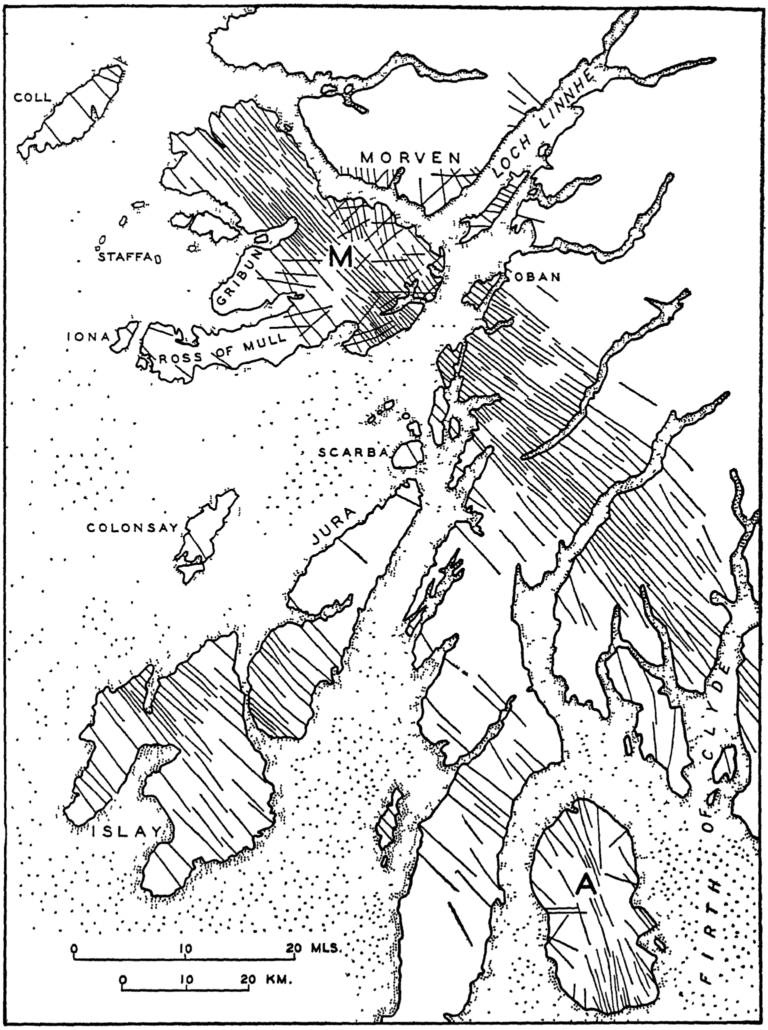

FIG. 21.—Map of dike swarm in western Scotland. *M*, focus of the Mull swarm; *A*, focus of the Arran swarm. (*After Mull memoir, Geol. Survey Scotland*, 1924, *p*. 357.)

regularly defined, and penetrates the surrounding rocks in a wavy thread-like fashion, this irregular protrusion is called a *vein*.[1]

[1] J. B. Jukes, Manual of Geology, edited by A. Geikie, London, 1872, p. 263.

According to A. Geikie's definition, a *contemporaneous vein* "forms part of the igneous rock in which it occurs but belongs to a later period of consolidation than the portion into which it has been injected."[1]

4. Apophyses or tongues are dikes or veins which, either directly or by inference from field relations, can be traced to larger intrusive bodies as the source of magmatic supply of dike or vein.

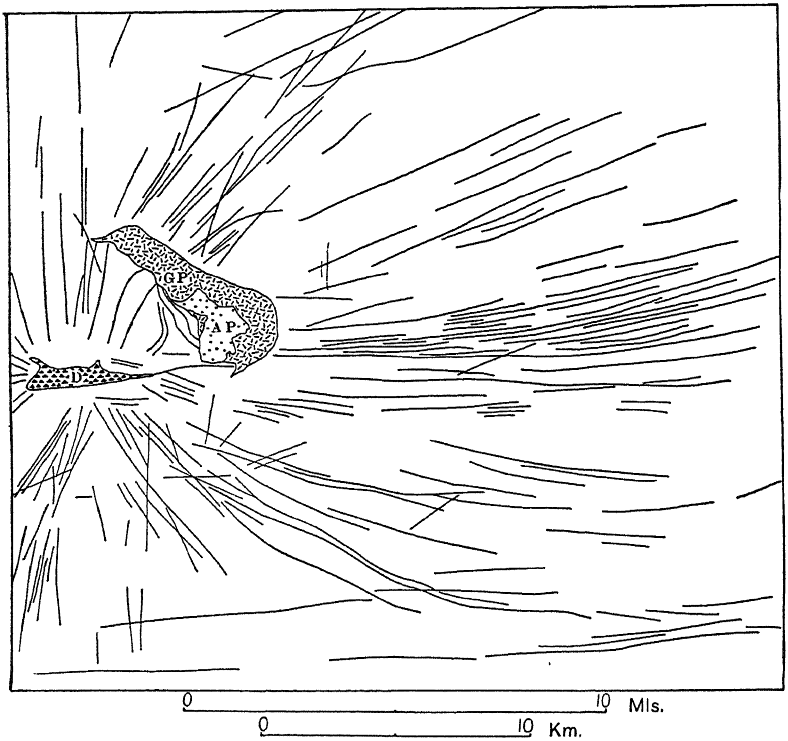

FIG. 22.—Map of dike system, apophysal from stocks, Colorado. *GP*, granite porphyry; *AP*, augite-granite porphyry; *D*, augite diorite. (*Spanish Peaks folio, No. 71, U. S. Geol. Survey*, 1901.)

5. Ring Dikes.—The conception of a ring dike (Fig. 23) was first published by Clough, Maufe, and Bailey in their classic Survey memoir on the Glencoe district, Scotland. However, the name originated in the memoir on the island of Mull. The authors of this book defined it thus:

> A ring dyke is a dyke of arcuate outcrop, where there is good reason to believe that the arcuate form is significant rather than accidental. Only in

[1] A. Geikie, Text-book of Geology, 4th ed., London, 1903, p. 738.

rare instances are ring dykes so completely developed as to show an entire ring-outcrop.[1]

The most perfect example in Mull is that composed of the Loch Ba felsite (thick, black ring in Fig. 24). It has a fairly continuous outcrop, the width ranging up to 400 meters. The dike dips steeply, with suggestions of a general outward inclination. A considerable number of other **simple** and **differentiated** ring dikes, separated by "screens" of country rock are associated with this remarkable body.

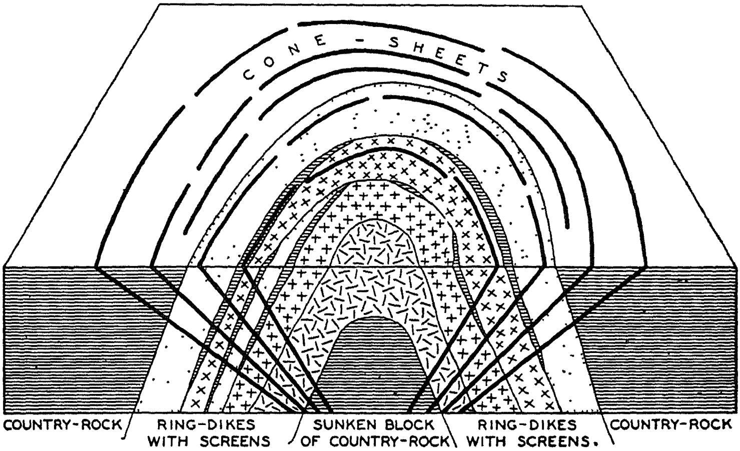

FIG. 23.—Block diagram to illustrate mutual relations of ring dikes of differing composition and dates of injection (*stipple, crosses, hachures*), screens (*shaded*), a very late set of cone sheets (*heavy black lines*), and country rock (*shaded*, in section). (*After J. E. Richey, Trans. Geol. Soc. Glasgow, vol.* 19, 1931, *p.* 48.)

The peninsula of Ardnamurchan furnishes excellent illustrations of simple ring dikes (Fig. 25) and of a **composite** ring dike, that is, one showing successive injections of different kinds of magma into a single break in the country rocks (Fig. 26). Ring dikes are found also at Glencoe, in the islands of Skye and Arran, in the Mourne Mountains, the Carlingford district, and the Slieve Gullion district. Tyrrell describes a small-scale example at Carskeoch Hill, Ayrshire. Analogous, if not essentially similar, intrusions have been mapped by Shand at the Pilandsberg, Transvaal, by Kingsley in the Ossipee Mountains, New Hampshire, and by Gilluly at Step Mountain, Utah.[2]

[1] E. B. Bailey and others, Tertiary and Post-Tertiary Geology of Mull, etc., Edinburgh, 1924, p. 306.

[2] For a general statement regarding the British examples, see H. H. Thomas in the Scottish Survey memoir on Ardnamurchan, North-west Mull, and Coll, 1930, p. 58. See also G. W. Tyrrell, The Geology of Arran, Memoir Geol. Survey Scotland, 1928, p. 9; Trans. Geol. Soc. Glasgow, vol. 18, 1928, p. 264. J. E. Richey and H. H. Thomas, Quart. Jour. Geol. Soc. London, vol. 88, 1932, p. 776. S. J.

According to Thomas,

The general theory of subsidence as originally enunciated for Glencoe, appears to be the only one that explains the observed facts, and therefore it is assumed that most of the plutonic rocks of the British Tertiary Centres have risen into their respective positions as the result of the subsidence into a

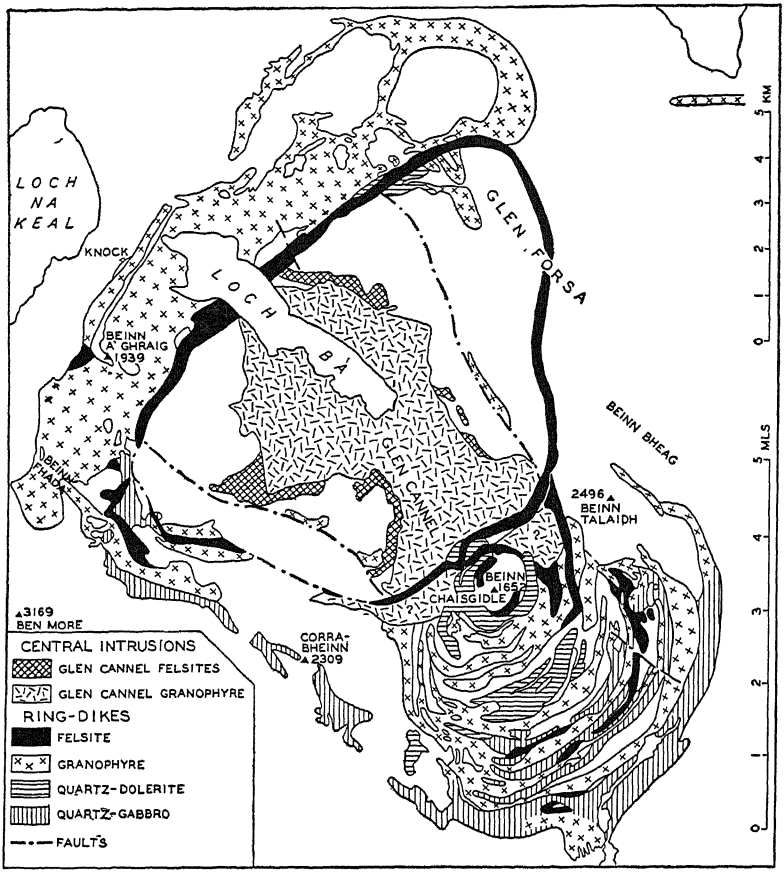

FIG. 24.—Map of ring dikes in the Island of Mull. (*Mull memoir, Geol. Survey Scotland*, 1924, *p.* 307.)

magma-reservoir of a steep-sided conical crustal block. Such subsidence would cause the welling up of magma into the fissure that bounds the subsiding mass, and, if the ring-fracture reached the surface, a central type of lava eruption would be likely to ensure, as in the case of the South-east Caldera of Mull. If, however, the subsiding block was detached from the under part

Shand, Trans. Geol. Soc. South Africa, vol. 31, 1928, p. 97. L. Kingsley, Amer. Jour. Science, vol 22, 1931, p. 129. J. Gilluly, Prof. Paper 173, U. S. Geol. Survey, 1932, p. 61 and Plate 10A.

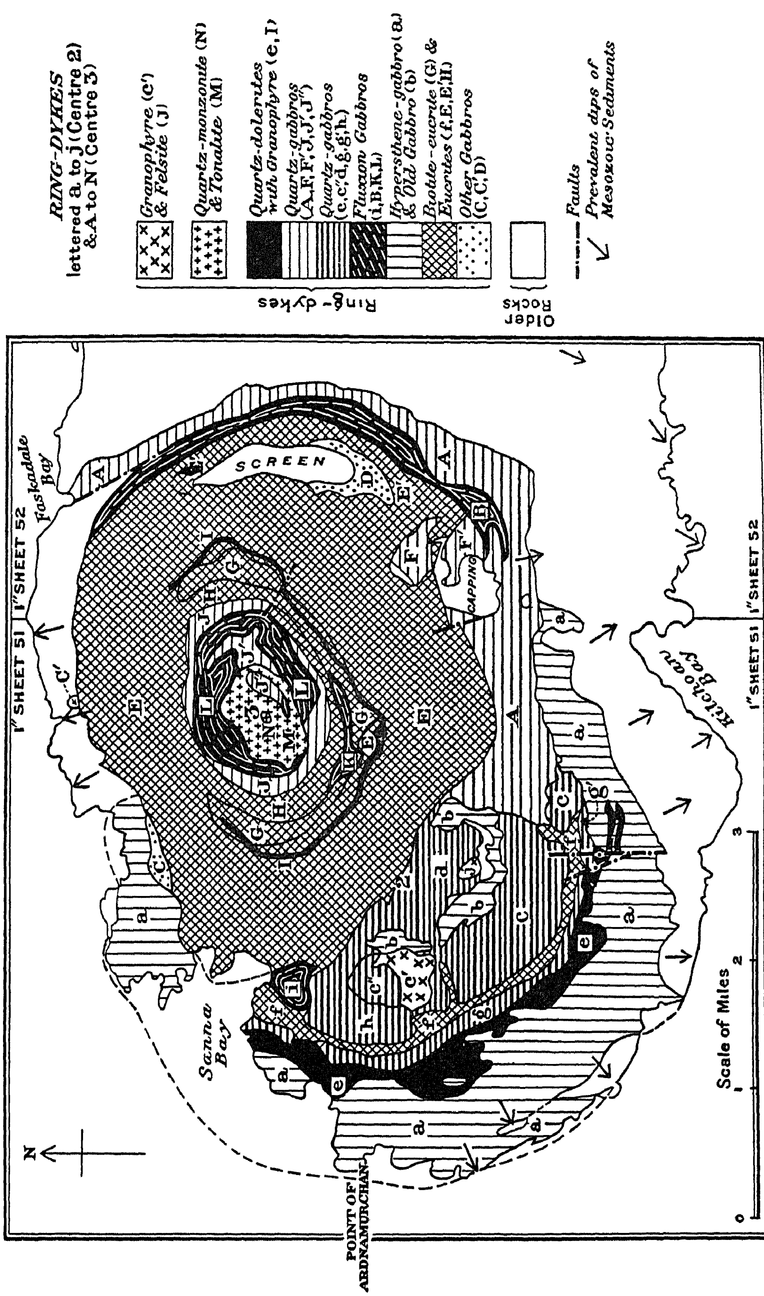

FIG. 25.—Map of ring dikes in Ardnamurchan, Scotland (*Copied from Ardnamurchan memoir, Geol. Survey Scotland*, 1930, p. 200.)

of the solid crust, the fractures would not of necessity reach the surface and then the space formed over the subsiding mass would be filled with magma that would be continuous with the lateral steep-sided ring-dyke intrusion, but be more or less horizontal in disposition. Such conditions were claimed for certain granites of the Glencoe district and appear to have been fulfilled in the Red Hills of Skye and the Mourne Mountains, and also in Ardnamurchan and Mull, where cappings of rock older than the intrusions upon which they rest suggest more or less horizontal extensions from ring-dykes beneath a roof of country rock. . . .

It would appear, in contradistinction to cone-sheets, that the formation of ring-dyke fissures and the concurrent intrusion of magma are independent of excessive magmatic pressure but are consequent on crustal collapse.[1]

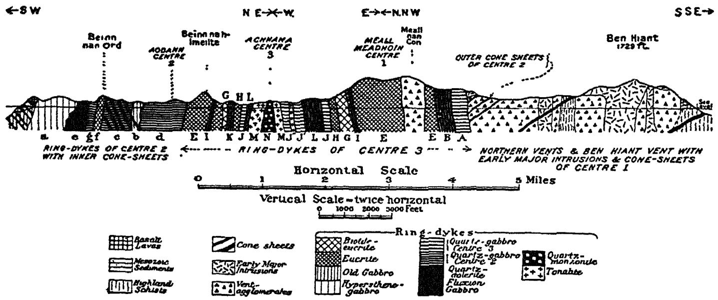

FIG. 26.—Section of ring dikes, Ardnamurchan. (*Ardnamurchan memoir, Geol. Survey Scotland*, 1930, *p.* 205.)

Figure 5 of the Richey-Thomas memoir on Ardnamurchan, Northwest Mull, and Coll graphically represents the inferred relations of ring dike and cone sheets to a magma reservoir. In the Mull memoir (page 11) E. M. Anderson had offered the mechanical explanation.

6. Cone Sheets.—To describe this class of intrusions we cannot do better than use the summary statement by Thomas:[2]

A most important class of centralized intrusion of hypabyssal type was first detected by Dr. Harker in Skye, when he discovered and mapped in the Cuillin Hills a great group of centrally inclined basic sheets. He demonstrated their circular distribution and regular inclination towards a focus situated within the great gabbro-intrusion of the Cuillins, and proved that, although younger than the gabbro, they were clearly related to the same intrusive centre. Such inclined sheets or cone-sheets, as they have been renamed in the "Tertiary Mull memoir" consist of relatively thin sheets, which, viewed as members of a suite, occupy conical fissures that have a common apex and common vertical axis. Generally the sheets are moderately open-spaced, but occasionally they may be so numerous and frequent as almost to obliterate the country-rock into which they have been intruded. The apex to which the sheets converge may be designated the cone-sheet focus.

[1] H. H. Thomas, Ardnamurchan memoir, pp. 58, 59.

[2] Pp. 56–58 of the Ardnamurchan memoir.

Their outcrops, taken collectively, may be idealized as a series of concentric circles [Fig. 5 of memoir]. The average inclination of the cone-sheets is as a general rule about 45°. There is, however, a definite tendency for sheets nearer the centre to be more highly inclined than those farther away (Skye, Mull, Ardnamurchan). The central area around the axis is always devoid of cone-sheets. . . .

From the nature of cone-sheets it is practically certain that their formation is due to an excess of magmatic pressure acting vertically upwards upon a relatively thin crustal covering, in a successful attempt on the part of the

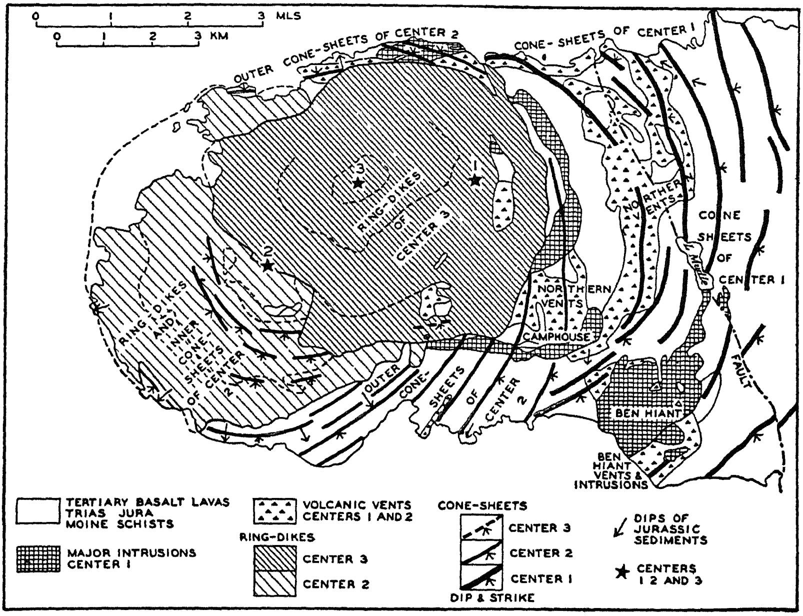

FIG. 27.—Map showing general distribution of ring dikes and cone sheets of centers 1, 2, and 3, Ardnamurchan. (*Ardnamurchan memoir*, *Geol. Survey Scotland*, *Plate* II.)

magma to raise its roof. Such was the suggested explanation of the formation of cone-sheets put forward by E. M. Anderson in 1924 (Mull), and all later work has tended towards its confirmation. . . .

The magma that filled any particular suite of cone-sheet fissures was remarkably constant in composition, and this proves beyond doubt that all the fissures of any one set of cone-sheets were filled from a common source. Different suites, however, and cone-sheets related to different centres, usually show some magmatic variation.

Examples of *simple, differentiated, multiple,* and *composite* cone sheets are represented in the British field (Figs. 27, 28).

7. Volcanic Necks.—The solid lava occupying a volcanic vent must be considered as intrusive into the wall rock, but illustration of necks will be postponed to Chapter VIII.

8. Bysmaliths.—Iddings described a "bysmalith" as an injected body filling a "more or less circular cone or cylinder of strata, having the form of a plug, which might be driven out at the surface of the earth, or might terminate in a dome of strata resembling the dome over a laccolith." The downward termination of the original type

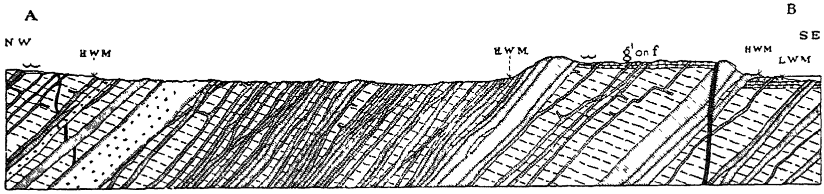

FIG. 28.—Section of outer cone sheets of center 2, Fig. 27. Basic cone sheets (*shaded*) and basic cone sheets with acid interiors (*crosses*), cutting Moine schists (*broken, wavy lines*); older basic dikes (*black*); Mesozoic sediments (g' and f). Length of section 820 meters. (*Ardnamurchan memoir, p.* 175.)

bysmalith (Mt. Holmes) is found at a hypothetical Archean floor on which the porphyry of the bysmalith rests. This body is sectioned in Plate 5 of Monograph 32, part 2, of the United States Geological Survey, 1899.

9. Ethmoliths.—Salomon has interpreted the tonalite of the Adamello group as an injected, crosscutting body. The described

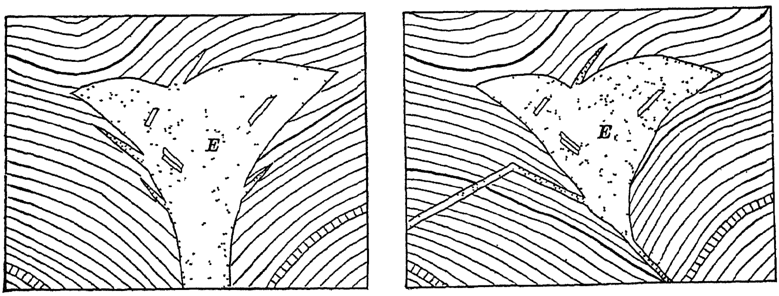

FIG. 29.—Diagrammatic section illustrating an ethmolith (E), with alternative suggestions as to the nature of its feeding channel. Stratification of invaded sediments shown by lines. (*After W. Salomon, Sitzungsber. k. preuss. Akad. Wiss., vol.* 14, 1903, *p.* 310.)

structural relations and mode of intrusion are those of the chonoliths; yet the form of the whole body as deduced from its outcrop is, in Salomon's opinion, definite enough to warrant a distinct name. He has accordingly called this body an "ethmolith" (literally "funnel rock").[1] It is defined as a plutonic mass that narrows downward, and is so situated that the younger beds of the (sedimentary) country rock are bent down into contact with the igneous body (see Fig. 29; also

[1] W. Salomon, Sitzungsber. k. preuss. Akad. Wiss., phys.-math. Kl., vol. 14, 1903, p. 310.

the map on page 48 of O. H. Erdmannsdörffer's "Grundlagen der Petrographie," 1924).

Du Toit describes a gabbro ethmolith at the Tugela River, Natal.[1] Gerth thinks that some of the "stocks" of the Argentine cordillera narrow downward and are ethmolithic.[2] According to Balk, the noritic mass of Peekskill, New York, is a complex funnel-shaped injection which also enters this category.[3]

10. Sphenolith.—This term was invented by Burckhardt to distinguish the special form and relations of the dacitic intrusion at Las Parroquias, Mexico.[4] This body is clearly of the injected class. It is partly concordant, like a thick sill, and partly discordant. The country rocks have been displaced even to overturning and some of the movement is to be credited to pressure from the magma itself.

According to Harker, the mass of quartz porphyry near Piatigorsk, Caucasus region, is of somewhat similar nature.[5]

11. Erdmannsdörffer has coined the word **akmolith** to describe the kind of intrusive body which, according to Steinmann, is dominant in the southern Andes. Steinmann assumed that, during the tight folding of the visible sedimentary country rocks, these were sheared quite away from, and lifted above, an underlying terrane which did not take part in the folding. The space between was filled, at equal pace with the folding and updoming, by salic magma. When the folding reached the isoclinal stage, this magma was still able to penetrate the roof sediments in lit-par-lit fashion. The resulting knifelike apophyses are conspicuous in the visible roof rocks, and for this reason the name "akmolith," rooting in the Greek word for (cutting) edge, was invented. A body of this type is thus definitely floored and, while locally concordant with the country rocks, must be classed with the discordant injections.[6] In the nature of the case the objective reality of this type of intrusion is not easily demonstrated.

12. The term **harpolith** originated with Cloos, who found his types in Silesia. It means a crosscutting body of sickle shape, resembling in form, though not in structural relations, a tilted phacolith. A harpolith is assumed to have been injected into previously deformed beds of rock and then with the latter to have been stretched horizontally in the direction of maximum orogenic displacement. Thus the feeding channel is typically situated beneath one edge of the sickle

[1] A. L. du Toit, Trans. Geol. Soc. South Africa, vol. 21, 1918, p. 64.

[2] H. Gerth, Geol. Rundschau, vol. 17a, 1926, p. 89.

[3] R. Balk, Neues Jahrb. f. Mineralogie, etc., B.B. 57, 1927, p. 259.

[4] C. Burckhardt, Guide, Cong. Géol. Internat. Mexico, 1906, part 26, p. 33.

[5] A. Harker, The Natural History of Igneous Rocks, New York, 1909, p. 71.

[6] O. H. Erdmannsdörffer, Grundlagen der Petrographie, Stuttgart, 1924, p. 53, with reference to Steinmann.

after this has been well exposed by erosion (Fig. 30). Cloos believes certain late Paleozoic granitic harpoliths of Germany to have been spread out along the interface between a folding and overriding cover of sediments and a stronger, more stable floor of gneiss.[1]

The voluminous anorthosite-gabbro mass of the Adirondacks has been called a laccolith, but Balk concludes that this body was injected along a gently inclined zone of shearing, incidental to plastic disrup-

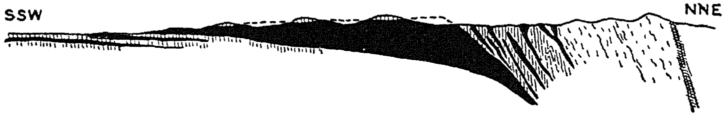

FIG. 30.—Diagrammatic section of a harpolith in Bavaria. *Black*, granite and diorite; *light shading*, older gneissic eruptives; *darker shading*, sediments and gneiss (Mischgneisse). (*Cloos.*)

tion of the whole crust of the earth. Thus conceived by Balk, the mass might be described as a blunt-ended harpolith.[2]

13. Sole Injections.—According to exponents of the nappe theory of the Alps, large bodies of basic magma, represented by the ophiolites and the "green rocks" of Suess, were early injected along the soles of some nappes. Examples are found in the greenstones which separate

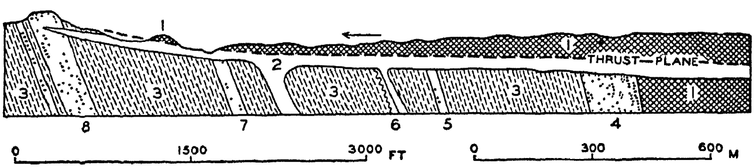

FIG. 31.—Section of gabbro sole-injection, Vredefort dome, Orange Free State. *1*, Old granite; *2*, gabbro; *3*, slates; *4*, Orange Grove quartzite; *5*, feldspathic quartzite; *6*, contorted bed; *7* and *8*, Upper and Lower Hospital Hill quartzites. (*After L. T. Nel, Geology of the Country around Vredefort, Memoir Geol. Survey South Africa,* 1927, *p.* 67.)

the Pennine and East Alpine nappes, and again in the limestone region of the Eastern Alps (Kober). Such intrusives, accompanying at least the embryonal stages of the major dislocations of the Alps, have been called *Ueberschiebungsapophysen.* A suitable synonym is "*sole injection.*" Argand recognizes these as genetically important also in the formation of the Himalayan, Iranian, and Carpathian arcs.[3]

[1] H. Cloos, Der Mechanismus tiefvulkanischer Vorgänge, Braunschweig, 1921, pp. 47, 84; Das Batholithenproblem, Berlin, 1923, p. 61; Geol. Rundschau, vol. 14, 1922, p. 19 (reference for Fig. 30).

[2] R. Balk, Min. u. petr. Mitt., vol. 41, 1931, p. 308; Jour. Geol., vol. 38, 1930, p. 289.

[3] E. Argand, Compte Rendu, Cong. Géol. Internat. 13th session, Liege, 1924, pp. 348–353. Compare R. Staub, Der Bau der Alpen, Berne, 1924, Tafel 29; E. Suess, La face de la terre (trans. by E. de Margerie), Paris, vol. 3, 1918, pp. 1501–

Where the soles are concordant with the bedding of the rocks, sole injections naturally tend to be concordant, but in general they seem better classed with the discordant injections. A small example in the Vredefort area has been studied by Nel (Fig. 31). There a sheet of gabbro was injected along a thrust plane between steeply dipping Witwatersrand sediments and overlying granite.[1]

14. Chonoliths.—There remains for distinction a class of injected igneous bodies which are not included among the above-mentioned categories. During the dislocation of rock formations, potential cavities are formed within the earth's crust. These are occasionally filled with igneous magma squeezed into the individual cavity from below, from the side, or, it may be, from above. Dikes, sills, and bodies of laccolithic form (though not strictly of the laccolithic mode of intrusion, as designated by Gilbert) may thus originate. Yet very often the shape of the intruded mass is so irregular, and its relations to the invaded formations so complicated, that the body cannot be classified in any of the divisions so far named. Again, irregular injected bodies of a similarly indefinite variety of form are due to the active crowding aside and mashing of the country rock, which is forced asunder by the magma under pressure. Or, thirdly, such bodies may be due to a combination of the two primary causes—orogenic stress preparing space for injection, and dislocating pressure from the magma itself.

The number and total volume of these irregular intrusions possibly rival the number and volume of all true laccoliths.

For such irregular intrusions the name "laccolith" cannot be used, since that term denotes a definite form and also implies a more restricted mode of injection than that here conceived. Hence the author has suggested the word "chonolith" (Greek *chonos*, a mold). The magma of a chonolith fills its chamber after the manner of a metal casting in its mold. Like a casting, the chonolith may have any shape.

One cannot be entirely satisfied with this invention. Etymologically it errs by being too broad, since laccoliths, sills, and other named injections are bodies molded against their wall rocks. This objection

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1505, where is given an illustrated summary of von Krafft's work on the amazing exotic, "Tibetan" blocks of limestone that are inclosed in what appears to be an extremely thick sole injection of diabase and other basic material. This magma is supposed to have traveled hundreds of kilometers, measured in the horizontal direction.

[1] L. T. Nel, The Geology of the Country around Vredefort, Memoir Geol. Survey South Africa, 1927, p. 67. E. H. Kranck (Acta Geographica, vol. 4, No. 2, 1932, p. 42) thinks the Patagonian ophiolites were probably injected during the earlier stages of the Cordilleran folding and are thus homologous with the Alpine greenstones as interpreted by Suess, Argand, and Kober.

is more or less formal and not so important as the fact that the definition includes masses formed under two highly contrasted conditions. In the one case the magma is active, like the liquid of a laccolith; in the other, it is largely or wholly passive during intrusion. However, the general impossibility of distinguishing the two conditions in Nature renders a *Sackname* useful to the field geologist. It is, of course, not intended that the use of this term shall discourage the invention of additional descriptive names for injected bodies. So far as new classes become recognized and named, the range of the chonolithic class, as covering all the injected bodies of irregular shapes will be narrowed. If the day ever comes when the essential mechanism of each injection becomes understood, the chonolithic bodies will merit more significant names in systematic classification. Meanwhile in spite of its shortcomings, the blanket name chonolith can serve a useful purpose. As above noted, for example, it can be employed in many cases where bodies have been described as "laccoliths," though these masses have neither the forms nor demonstrably the mode of intrusion of true laccoliths. Such overloading of Gilbert's term decidedly injures it for scientific purposes.

In still another direction the somewhat negatively defined word chonolith has value; its use permits of a clean-cut distinction in nomenclature between irregularly shaped, crosscutting, but definitely injected masses and those irregularly shaped, crosscutting masses—subjacent batholiths and stocks—whose mode of emplacement continues to be a matter of speculation. The multiplication of names is, of course, to be avoided as far as possible, but evidently what petrology has long needed is a proper expansion of its vocabulary. Those who have already decided that subjacent bodies are all pure injections with solid floors are likely to agree with Iddings, Cloos, and von Wolff that the term chonolith is "superfluous." Others, more sensible to the enigma represented by the batholiths, will be inclined to conclude that something like this new coinage is demanded in the interests of clear, unprejudiced thinking.

A chonolith may be thus defined: a discordant igneous body (*a*) injected into dislocated rock of any kind, stratified or not; (*b*) of shape and relations irregular in the sense that they are not those of a dike, sheet, laccolith, bysmalith, ethmolith, sole injection, or neck; and (*c*) composed of magma passively squeezed into a subterranean orogenic chamber or actively forcing apart the country rocks.

The chamber of a chonolith may be enlarged to a subordinate degree by contact fusion on the walls, or by magmatic "stoping."

A preliminary paper (1905) on this subject contains reference to many bodies which seem to belong to the chonolithic class. The cases

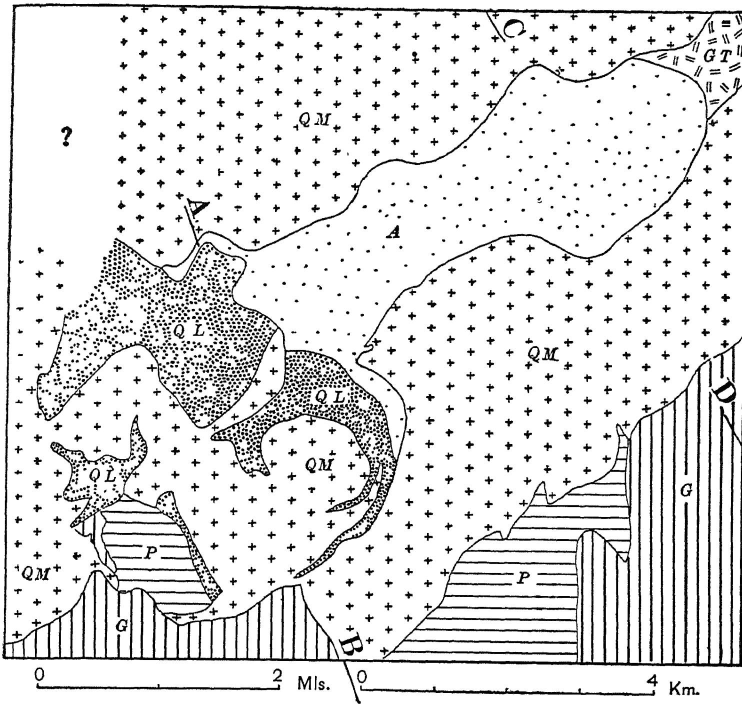

FIG 32.—Plan of chonoliths of quartz latite porphyry (*QL*) and andesite (*A*) cutting quartz monzonite and quartz monzonite porphyry (*QM*), post-Carboniferous granite (*GT*), Paleozoic sediments (*P*), and Pre-Cambrian granite (*G*); Monarch and Tomichi districts, Colorado The chonoliths are probably of Tertiary age. (*After R. D. Crawford, Bull.* 4, *Colorado State Geol. Survey*, 1913, *Plate* 2.)

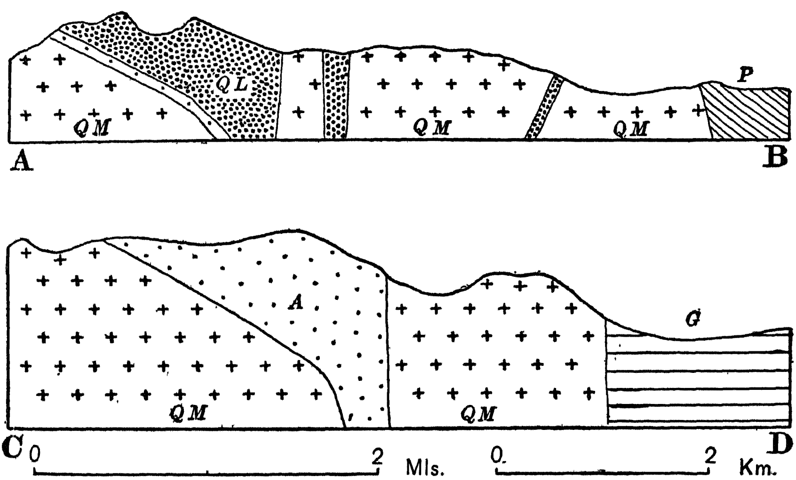

FIG. 33.—Sections along the lines *A–B* and *C–D* in Fig. 32. Underground contacts partly determined by mining.

there cited were discussed simply from the maps, sections, and reports of government geologists, working in Montana, the State of Washington, and South Dakota. Other instances are illustrated in Figs. 32 and 33. Still others have been described as occurring in British Columbia, Pennsylvania,[1] New South Wales,[2] and South Australia.[3] The large gabbro-norite mass of the Cuyamaca region, California, is referred by Hudson to the chonolithic class.[4]

Clough, Maufe, and Bailey have explained the emplacement of some Scottish pluglike masses of granite by the sinking of cylindrical crust blocks along ring fractures, the magma rising *pari passu* along

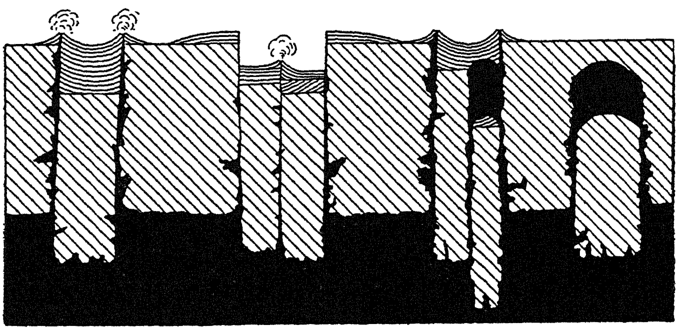

FIG. 34.—Diagram illustrating various types of cauldron subsidence, with and without extrusions of lava at the earth's surface. Crust, *diagonal shading,* substratum and intrusions, *solid black.* (*After C. T. Clough, H. B. Maufe, and E. B. Bailey, Quart. Jour. Geol. Soc. London, vol.* 65, 1909, *p.* 670.)

the fractures and occupying the spaces vacated by the sinking blocks. These did not founder in a general magmatic layer but became stabilized within the solid crust of the earth (Fig. 34). Hence the intrusions should be classed with true crosscutting injections rather than with the more problematical subjacent bodies. The classic examples of such results of "cauldron subsidence" are those of Glencoe (Fig. 35), Etive, and Ben Nevis.[5] They may be described as chonoliths of ring-dike form, if the mode of intrusion has been correctly diagnosed.

Richey assumes a somewhat similar mechanism for the Mourne granites of Ireland (Fig. 97), as well as for the granite of Ardnamurchan.[6]

[1] F. Bascom, Bull. 360, U.S. Geol. Survey, 1909, p. 663.

[2] E. C. Andrews, Rec. Geol. Survey New South Wales, vol. 8, part 3, 1907 (reprint), p. 13.

[3] C. E. Tilley, Trans. Roy. Soc. South Australia, vol. 43, 1919, p. 341.

[4] F. S. Hudson, Bull. Dep. Geol. Univ. California, vol. 13, 1922, pp. 181, 207.

[5] C. T. Clough, H. B. Maufe, and E. B. Bailey, Quart. Jour. Geol. Soc. London, vol. 65, 1909, p. 669; Ben Nevis-Glencoe memoir, Geol. Survey Scotland, 1916, p. 107. See also Mull memoir of the same Survey, 1924, p. 9.

[6] H. E. Richey, Quart. Jour. Geol. Soc. London, vol. 83, 1928, p. 653; see H. H. Thomas in discussion, p. 688.

The granophyric Slaufrudal "stock" of Iceland may be another instance. This largest of the known intrusive masses of the island is well exposed, is crosscutting, and is clearly due to the mechanical

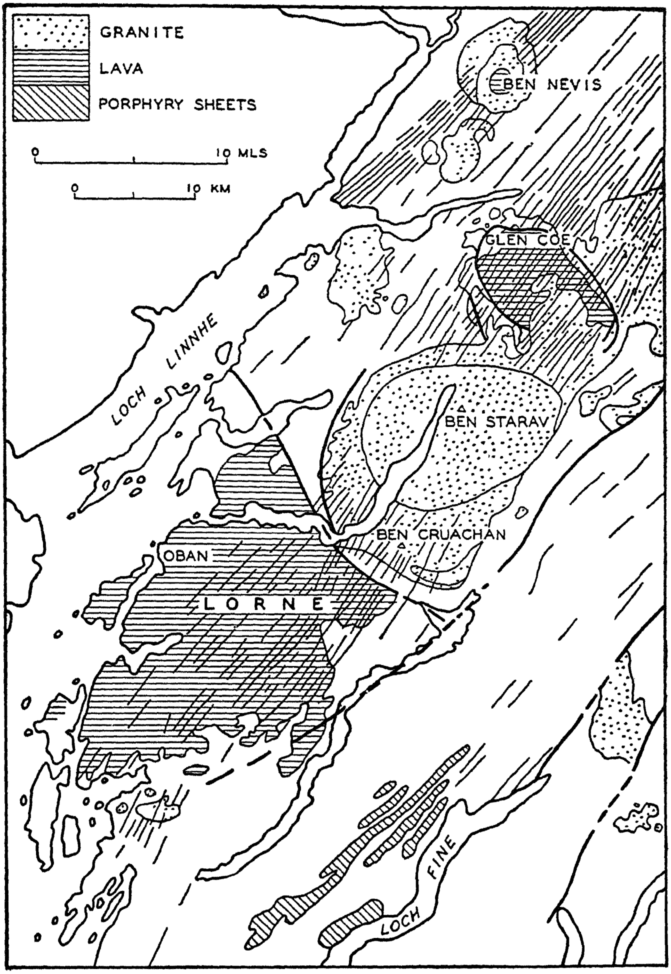

FIG. 35.—Map of the Etive and Ben Nevis granite complexes, loci of assumed cauldron subsidences; also associated dike swarm. Heavier lines show faults. (*Geology of Ben Nevis, etc., Memoir Geol. Survey, Scotland,* 1916, *p.* 90.)

replacement of the nearly horizontal lava flows which constitute the country rocks. There is some reason for believing that the

. . . replaced mass sank "en bloc" rather than by piecemeal stoping. The distinct layering of the intrusion indicated intermittent subsidence, the stock growing by the addition of successive sills. The presence of chilled phases within the mass shows that considerable time elapsed between the intrusions, and the growth of the stock must have been a long process. . . . The magma

was under no great pressure, but welled up owing to gravitational displacement by the sinking block.[1]

If the block now forms the floor of the intrusion, this must be classed with the injected bodies.

Cloos explains the discordant replacing relations of the Erongo granite, Southwest Africa (Fig. 102), and of some German granites by floor subsidence and expressly states that stoping, differential density, was not the cause of the sinking. If he is right in this, we have so many more illustrations of the principle embodied in the chonolith idea.

[1] H. K Cargill, L. Hawkes, and J. A. Ledeboer, Quart. Jour. Geol. Soc. London, vol. 84, 1928, p. 521.

CHAPTER VII

SUBJACENT BODIES

Definitions

The subjacent masses still lack any generally accepted explanation and deserve separate treatment. The difficulty of accounting for them is apparent: direct access to batholith or stock is necessarily limited to its upper part. Hence, almost as a matter of course, opinions regarding shape, volume, and mode of emplacement have diverged widely. Though this complex problem lies at the root of any sound explanation of eruptive rocks in general, we can make little progress with it unless we go beyond the facts observed in batholithic regions. From these facts alone, inference cannot carry us to the goal. To reach it, there must be correlation with the results of quite different studies, the subjects of which include the nature of the outer shells of the earth, the thermal condition of the planet, orogeny, eruptive sequences, syngenesis of igneous-rock species, and other major topics of geology and geophysics. In fact, a good understanding of the subjacent masses is to be founded upon a broad synthesis, a satisfactory theory of the earth as a whole. Following chapters will be much occupied with such speculative questioning. The present one is designed to summarize observational facts derived from the subjacent bodies themselves. The effort has been made to state the essential facts without prejudice from any theory. Definitions to correspond will be offered.

The term **batholith** was introduced by Suess to designate the larger subjacent bodies at a time when his conception of these was undergoing noteworthy changes. His final definition, freely translated, is

> A batholith is a stock-shaped or shield-shaped mass intruded as the result of the fusion of older formations (*Durchschmelzungsmasse*). On the removal of its rock-cover and continued denudation, the mass either holds its diameter or grows broader to unknown depths (*bis in die ewige Teufe*).[1]

The definition has a strongly subjective element. Many authors have since used the name to denote the large bodies otherwise referred to as "central granites," "intrusive mountain cores," *Fussgranit*, etc.

[1] E. Suess, Sitzungsber. k. und k. Akad. Wiss., Wien, vol. 104, 1895, p. 52. See also "La face de la terre," vol. 3, Paris, 1918, p. 1473.

We shall later note the possibility that some of the major granitic masses of the early Archean may conform to Suess's definition of batholith, but chemical considerations show this definition to be inapplicable to post-Archean granites of large bulk.

In this book "batholith" will mean typically a large, crosscutting, subjacent intrusive mass, that is, one with no visible or clearly inferable floor of older solid rock, and hence showing no direct evidence of having been emplaced by simple injection into the earth's crust. The negative aspect is emphasized in order to express the actual state of the best geological opinion, and also to bring the problem of origin into the foreground.

Some large, crosscutting intrusive masses have been mapped as batholiths in the sense of being bottomless, without solid floors at the time of intrusion. Yet close examination has made certain or highly probable their possession of floors and their emplacement by pure injection. As suggested in the preceding chapter, such bodies are profitably classed with chonoliths or other "injected" types, rather than with the subjacent.

On the other hand, large plutonic masses without visible floors have been arbitrarily classed as "laccoliths" or "sheetlike" bodies without any warrant from direct field observation.[1]

[1] As phrased by T. C. Chamberlin, the Planetesimal theory of the earth's origin implies a solid floor for every eruptive mass. Advocates of that theory have felt in duty bound to explain all visible granitic masses as pure injections. On the other hand, even H. Cloos (Fennia, vol. 50, No. 2, 1928, p. 4), a leading field student of many granite massifs of Central Europe, all of which he regards as injected bodies, recognizes under the name *Periklinalplutone* another class of downwardly enlarging intrusions. He agrees that this class awaits explanation. Some careless readers of his writings have jumped to the conclusion that Cloos explains all granite massifs as pure injections. In his own words (translated), "this is by no means the case," especially with massifs which are "normal and typical, including those with discordant contacts" (Tektonische Behandlung magmatischer Erscheinungen, Berlin, 1925, p. 7). R. Balk (Bull. Geol. Soc. America, vol. 36, 1925, p. 691) holds the same belief as Cloos about the German granites but considers them to be "offshoots from a large subjacent mass," nowhere as such exposed.

How interpretations differ is illustrated by the conclusions of workers in the Andes. While G. Steinmann and R. Hauthal described Andean granite masses as laccolithic, akmolithic or sheetlike, pure injections, J. A. Douglas (Quart. Jour. Geol. Soc., vol. 70, 1914, p. 46) prefers to describe them as batholiths. H. Gerth (Geol. Rundschau, vol. 17*a*, 1926, p. 62) found in the Argentine cordillera both ethmoliths and batholiths, laccoliths being quite subordinate. Another example: Barrell made the Marysville stock a classic type of the subjacent class. Cloos prefers to regard it as a simple injection, the argument being that Lawson had suggested the laccolithic nature of the much greater, adjacent, presumably parent mass, which Weed had named the "Boulder batholith." Even if Lawson's evidence for his view were compelling, Cloos's deduction lacks cogency (Das Batholithenproblem, Berlin, 1923, p. 13).

Characteristic Features

Like that of "subjacent mass," the definition suggested for batholith is abstract. If it were generally adopted, the future discussion of the great felsic massifs would be facilitated, because the naming does not, in advance, beg the question of origin. However, it is necessary to go beyond such a mere abstract statement and to review the characteristics of subjacent bodies.

All the essential features of batholiths, except size, are also represented in "stocks" and "bosses." These two terms are often used synonymously. According to its general meaning, **boss** should refer to stocks of nearly circular ground plan at the surface of exposure. **Stocks** are simply small batholiths. Fairly common usage confines the term batholith to those subjacent masses which, at the outcrop, cover more than 100 square kilometers or about 40 square miles; there is some convenience if subjacent masses of smaller area of outcrop be called stocks.

Since the field relations are similar throughout, the following description of the general features of subjacent bodies will be phrased usually in terms of batholiths alone, thus avoiding useless repetition. The more or less objective characteristics include

1. Location in orogenic belts, though this may not be true of some early Pre-Cambrian batholiths (Basement Complex).
2. Generally, elongation parallel to the tectonic axes of the mountain range.
3. Date of intrusion following, more or less closely, an antecedent period of mountain building.
4. Crosscutting relations to the country rocks.
5. An irregularly domical roof, commonly with projections downward and re-entrants upward.
6. Steeply inclined walls.
7. Relative smoothness of the walls.
8. Downward enlargement; no floor visible.
9. The appearance of having replaced the invaded formation during the intrusion.
10. Composition usually felsic; relatively homogeneous to visible depths.
11. Great volume with corresponding long magmatic life, slow cooling, considerable ultimate contraction, and resulting necessity of prolonged readjustments of the material of both batholith and intruded terrane.

Location in Zones of Mountain Building.—With few, if any, exceptions the post-Cambrian subjacent bodies are located in or close to orogenic belts. This is not due merely to the greater depth of erosion and consequently more perfect exposure of deep-seated formations in the mountainous regions. The denudation of some high areas, well removed from orogenic belts and characterized by the plateau (horizontal) type of structure, has been very profound, but

in no one of these has a batholith cutting the flat-lying sedimentaries yet been demonstrated.

In a given mountain chain, the abundance and observed sizes of batholiths tend to be directly proportioned to the intensity of the orogenic crumpling. These rules are illustrated by the North American Cordillera (Fig. 36). The largest and most numerous subjacent bodies

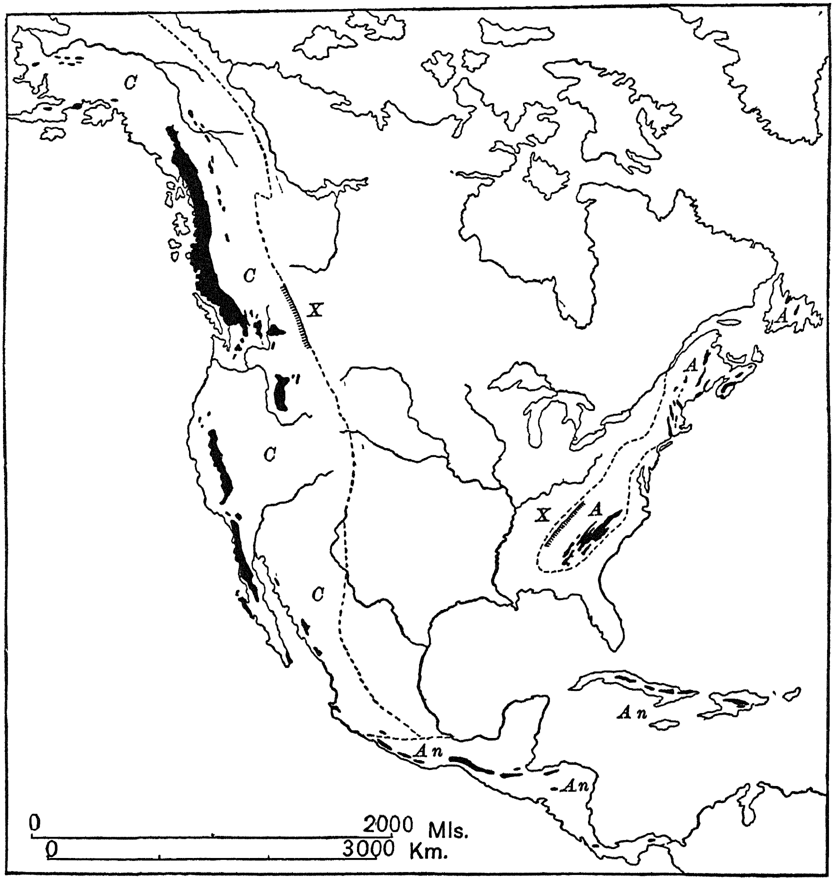

FIG. 36.—Map showing distribution of batholiths (*solid black*) in the North American Cordilleran (*C*), Appalachian (*A*), and Antillean (*An*) mountain systems. Large-scale overthrusting is demonstrated for zones marked with hachures and the symbol *X*.

occur in the western half of this belt, from Southern California to Bering Sea, where, on the average, the deformation of the invaded formations is much more advanced than in the eastern half of the huge belt. Similarly, while no subjacent body is known to cut the equally ancient Paleozoic strata in the open folds of Pennsylvania, the compressed folds of New England are penetrated by numerous post-Cambrian stocks and batholiths.

However, zones of intense crustal deformation by no means always include visible batholiths. Granitic rocks have comparatively small volume in the European Alps, the Carpathians, the Caucasus, the Himalayas, the New Zealand Alps, and the belt of Allegheny folds and thrusts. Partial explanation may lie in the failure of sufficient unroofing by erosion. Another important cause is suggested by the prevalence of strong orogenic thrusting in at least some of those belts. As a rule, batholiths are absent along sections where major overthrusts or underthrusts have been demonstrated. An illustration is found in the Alps, where no Tertiary granites appear among the great

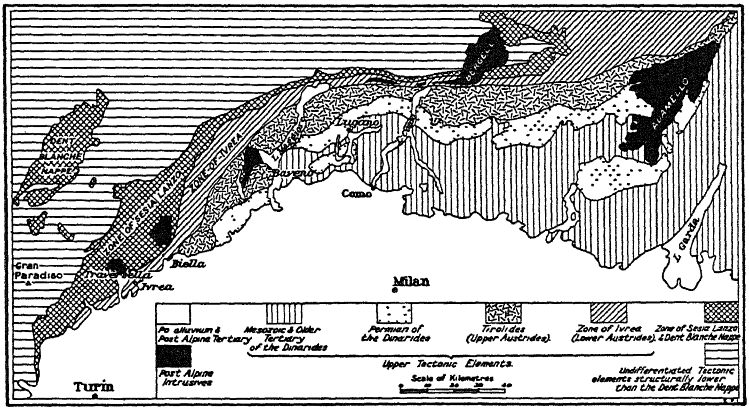

FIG. 37.—Map of the Alpine Tertiary batholiths, confined to the general region from which the major nappes moved in their northerly and northwesterly courses. (*From W. Q. Kennedy, Bull. Suisse de Minér. et Petr., vol.* 11, 1931, *p.* 79.)

nappes of Switzerland but do crop out along the "roots" of the nappes[1] (Fig. 37). The asymmetry of the Variscian chain is analogous, for there too batholithic magma rose at the "root" region and avoided the zone of strong thrusting of the nappe type.[2] A third example is the Canadian Cordillera, which lacks batholiths almost entirely in the eastern half, characterized by notable "overthrusts," and is specially rich in batholiths along the western half (see Fig. 36, where also the Appalachian case is indicated). Recently Kranck has described a parallel case in Tierra del Fuego, Patagonia.[3]

Again, visible batholiths with the present definition seem to be remarkably rare over wide stretches of the early Pre-Cambrian (Archean) terranes, though the rocks of these are so intensely deformed.

[1] *Cf.* R. Staub, Der Bau der Alpen, Beitr. z. geol. Karte d. Schweiz, N.F., Lief. 52, 1924, p. 23.

[2] F. E. Suess, Intrusionstektonik und Wandertektonik im variszischen Grundgebirge, Berlin, 1926, pp. 161, 239.

[3] E. H. Kranck, Acta Geographica, vol. 4, No. 2, 1932, pp. 80, 210*ff*.

The folded, thrust, and upended sediments and volcanic beds are penetrated by numberless bodies of granite, the dominant material of our batholiths, but in general the former intrusives are to be classed as injections—dikes, lit-par-lit sheets, sills, laccoliths, phacoliths, chonoliths, etc. The unexampled invasion of the crust by granitic magma during the early Pre-Cambrian appears to have been well under way before the upending of the still older, bedded rocks. To that earlier stage much of the lit-par-lit injection of granite is probably to be referred. Other concordant injections (phacoliths) of granite appear to have accompanied crosscutting intrusions during the latter, major deformations. Such at least is the opinion of several recent workers in the Archean.

In North America and Europe typically crosscutting batholiths seem to have been first developed, in large numbers at least, during comparatively late Pre-Cambrian time. Thus, the emplacement of the extensive crosscutting granites of the British Columbia Shuswap terrane followed the epoch of wholesale lit-par-lit injection in the region.[1] An important paper by Geijer emphasizes the generally concordant nature of most early Pre-Cambrian granites of Scandinavia, in contrast with the characteristically crosscutting relations of the associated "Serarchean" (late Archean) masses.[2]

Elongation Parallel to Tectonic Axes.—Where erosion has stripped off much of the cover, the longer axis of a visible batholithic mass tends to be nearly or quite parallel to the tectonic axis of the mountain-built zone where the mass is situated. This typical relation is, of course, likely to be more or less concealed if the removal of the cover

[1] R. A. Daly, Mem. 68, Geol. Survey Canada, 1915, p. 30.

[2] P. Geijer, Bull. Geol. Inst. Upsala, vol. 15, 1916, p. 47. Among the many other regions where the older Archean massifs of granite generally have concordant contacts may be mentioned: the Rainy Lake district of Ontario; the Hastings-Haliburton district of the same province; the Bradshaw region, Arizona; Finland (the *Antiklinalbatholithe* of P. Eskola, Fortschr. d. Mineralogie, etc., vol. 11, 1927, p. 106); Scotland (H. H. Read, Trans. Roy. Soc. Edinburgh, vol. 55, 1927, p. 351); Southwest Africa (E. Kaiser, Die Diamantenwuste Südwest-Afrikas, Berlin, 1926, p. 222); northwestern Rhodesia, where, according to R. Murray-Hughes (Quart. Jour. Geol. Soc. London, vol. 85, 1929, p. 117) the widespread, crosscutting Hook granite of Pre-Cambrian age invaded a much older, highly deformed complex with dominating lit-par-lit granites. In all these areas the larger granite masses of the relatively late dates are crosscutting.

See also N. Sundius (Sver. Geol. Unders. Arsbok, vol. 15, 1921, p. 115) and P. J. Holmquist (Bull. Geol. Inst. Upsala, vol. 15, 1916, p. 136), giving reference to Törnebohm and others who had appreciated the described structural contrast between the early and late Pre-Cambrian granites of Scandinavia.

I. S. Allison (Jour. Geol., vol. 33, 1925, p. 488) explains the magmatic rise of the comparatively late Pre-Cambrian, Giants Range granite of Minnesota by a combination of stoping and lit-par-lit injection.

has only begun; in such a case the exposure of the batholith is partly due to the accidents of denudation, and the shape of the intrusive has no direct relation to the ground plan of its outcrop.

Examples of parallelism between batholithic axes and the tectonic axes of the country rock are abundant. It will suffice to illustrate the rule by reference to the Cordilleras of both North America (Fig. 36) and South America (Fig. 38), the Hercynian Mountains of

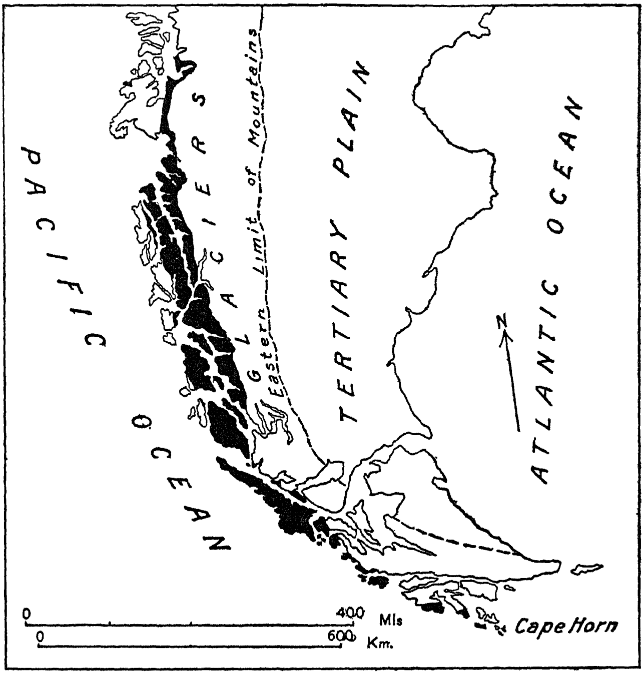

FIG. 38.—Map showing position of the great Patagonian batholith (*solid black*). Mapping approximate. (*After P. D. Quensel, Bull. Geol. Inst. Univ. Upsala, vol.* 11, 1911.)

Brittany (Fig. 106), Ireland, the Pyrenees (Fig. 39), the Ural Mountains, the Himalayas, the Atlas Mountains, the mountains of New South Wales and of New Zealand.

Time Relation to Mountain Building.—A second rule: each batholithic intrusion to visible levels was preceded by strong deformation of the corresponding orogenic belt. Of course, this does not mean that horizontal orogenic pressure had necessarily been wholly relieved at this stage of the intrusion. According to Bryan, this was actually the case with the granitic massifs of Queensland, where his evidence "suggests a quiet welling up (of magma) into a region of tension."[1]

[1] W. H. Bryan, Proc. Roy. Soc. Queensland, vol. 37, 1925, p. 68.

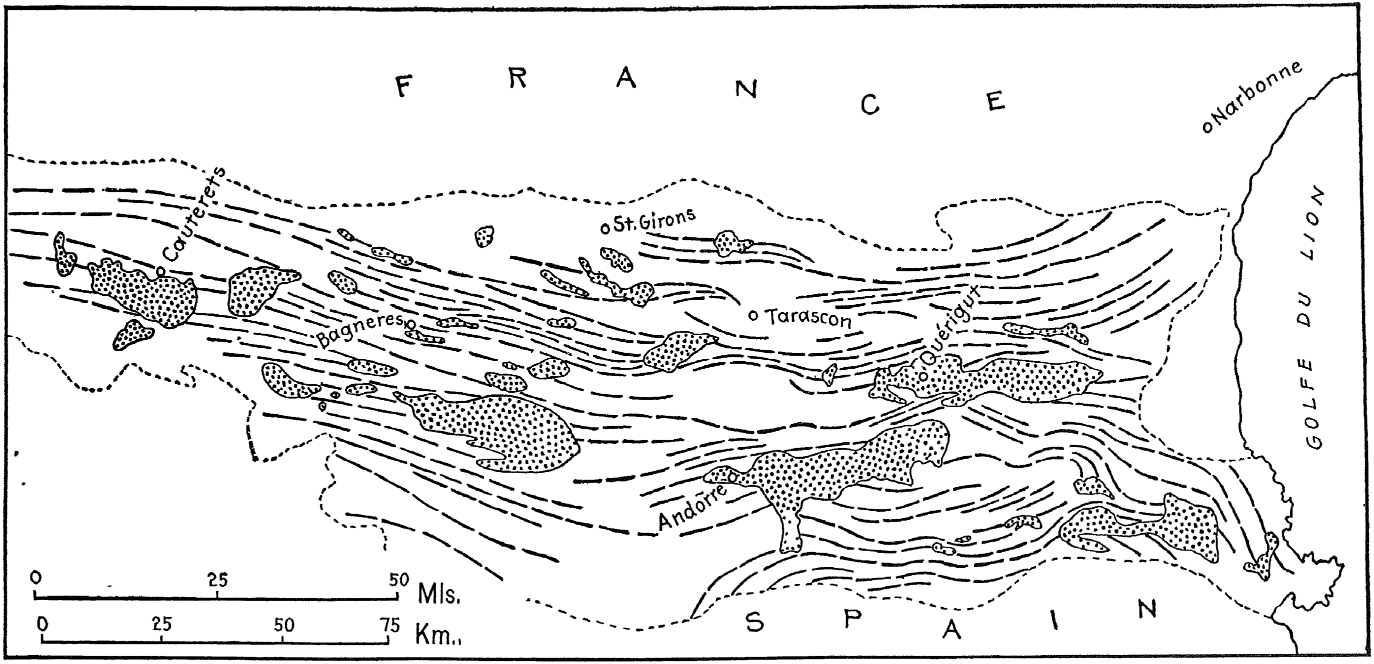

FIG. 39.—Map showing alinement of batholiths and stocks (*dotted*) in the Pyrenees, parallel to the orogenic axes, which are shown diagrammatically by broken lines.

Richardson, too, is not averse to the idea of tension in the orogenic belt when such granitic bodies are finally emplaced.[1] On the other hand, a number of bodies with most or all of the features of subjacent

TABLE 21*

Orogenic period	Corresponding batholithic period	Region
Epi-Huronian	Algoman	Canadian shield, Lake Superior region
Pre-Cambrian	Later Pre-Cambrian	Laramie Mountains, Wyoming
Epi-"Algonkian"	Later Pre-Cambrian	Black Hills, South Dakota
Epi-"Fernandan"	Later Pre-Cambrian	Central Texas
Epi-"Algonkian"	Later Pre-Cambrian	Colorado Front Range
Epi-Shuswap terrane	Later Pre-Cambrian	British Columbia
Epi-Vishnu	Later Pre-Cambrian	Grand Canyon, Arizona
"Lower Pre-Cambrian"	Serarchean	Sweden
Epi-Jatulian	Post-Jatulian interval	Sweden
Epi-Bottnian	Post-Bottnian interval	Finland
Epi-Kalevian	Post-Kalevian interval	Finland
Epi-Jatulian	Jotnian	Finland (Rapakivi, batholithic?)
Pre-Cambrian	Later Pre-Cambrian	Brittany
Pre-Cambrian	Later Pre-Cambrian	Mt. Lofty Ranges, South Australia
Post-Malmesbury	Later Post-Malmesbury	Cape Province
Early Pre-Cambrian.	Later Pre-Cambrian	Shan-Tung and other districts, China
Epi-Ordovician (?)	Taconic (?)	New York and New England
Caledonian	Devonian (?)	Oslo region
Caledonian	Devonian (?)	Western Norway
Epi-Devonian	Late Devonian or early Carboniferous	Canadian Appalachians
Post-Niagara	Late Silurian or Devonian	Fox Islands and Perry basin, Maine
Hercynian	Early Carboniferous	Brittany
Hercynian	Carboniferous	Germany
Hercynian	Carboniferous (or Permian?)	Devon, Cornwall
Carboniferous	Permo-Carboniferous	New South Wales
Carboniferous	Permo-Carboniferous	Queensland
Epi-Carboniferous	Permian	Pyrenees
Epi-Kanieri (Mesozoic?).	Post-Kanieri (Tertiary?)	New Zealand
Epi-Triassic	Late Jurassic	Caucasus
Late Jurassic	Close of Jurassic	Sierra Nevada
Late Jurassic	Close of Jurassic	Cascade Range
Late Jurassic	Late Jurassic or early Cretaceous	Coast Range of British Columbia and Alaska
Late Jurassic	Close of Jurassic	West Kootenay district, British Columbia
Late Jurassic	Close of Jurassic	Idaho, Montana
Epi-Cretaceous	Early Tertiary	Patagonian Cordillera
Epi-Cretaceous	Early Tertiary	New Mexico
Epi-Cenomanian	Early Tertiary or late Cretaceous	Pyrenees
Tertiary	Later Tertiary	Alps
Mid-Miocene	Late Miocene	State of Washington
Miocene	Pliocene	Yellowstone Park (batholithic?)

* In the table the prefix "epi-" means that the corresponding orogenic period directly succeeds the sedimentary period, the name of which follows the prefix in the first column. The "intervals" noted for the Swedish and Finnish cases are those which elapsed after the respective orogenic movements were completed and before the next recognized sedimentary series was deposited.

[1] W. A. Richardson, Geol. Mag., vol. 60, 1923, p. 124.

bodies, as here defined, have been themselves somewhat deformed by a continuance of the horizontal pressures of mountain building.[1]

Further, the rule stated does not mean that the beginning of any batholithic invasion of the crust postdates the main deformation of the corresponding belt of mountain building. Later on we shall see

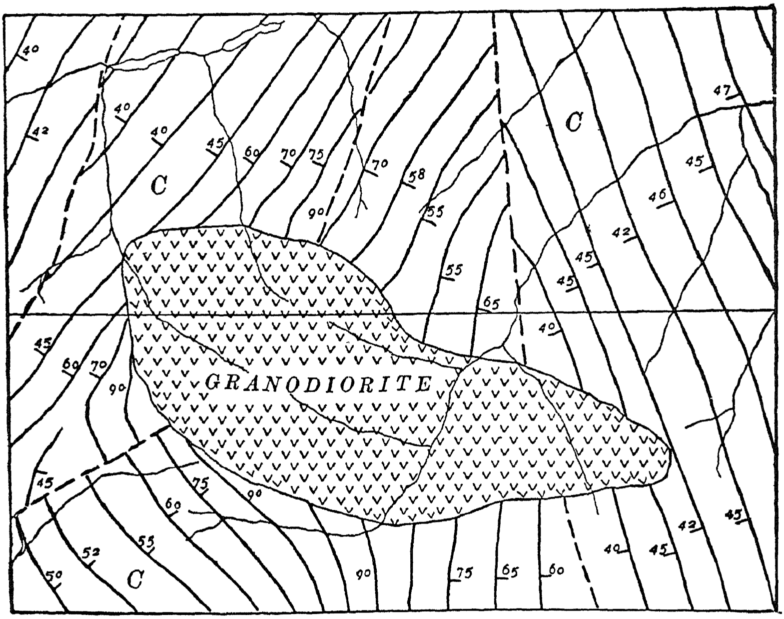

FIG. 40.—Map showing relation of the Castle Peak stock (British Columbia-Washington) to the invaded Cretaceous sandstones and argillites (*C*). Strike and dip lines *solid;* fault lines *broken;* figures show values of dip. Scale, 1:125,000 The horizontal line is the International Boundary.

the theoretical advantage of assuming coincidence in time for the beginning of such invasion and the beginning of active orogeny. For the present it suffices to stress the objective fact: the final stage in the emplacement of a batholith follows the maximum of orogenic deformation within the corresponding zone of mountain building. Table 21 exemplifies the rule.[2]

Crosscutting Relation to the Invaded Formations.—The common elongation of batholith or stock parallel with the strike of the inclosing mountain structure naturally involves some degree of lateral concordance between contact surface and the strike of the country rocks. Elsewhere truncation of planes of stratification or schistosity is usual. This crosscutting is sufficiently plain in ground plan (Fig. 40). Not-

[1] Well-known illustrations are to be found in the older literature as well as in the much discussed writings of H. Cloos and his school of workers on *Granittektonik.*

[2] *Cf.* R. Staub, Der Bau der Alpen, 1924, p. 245.

withstanding imperfect exposure by denudation, the crosscutting of roof and wall structures is sometimes evident in vertical sections (Figs. 46, 104).[1]

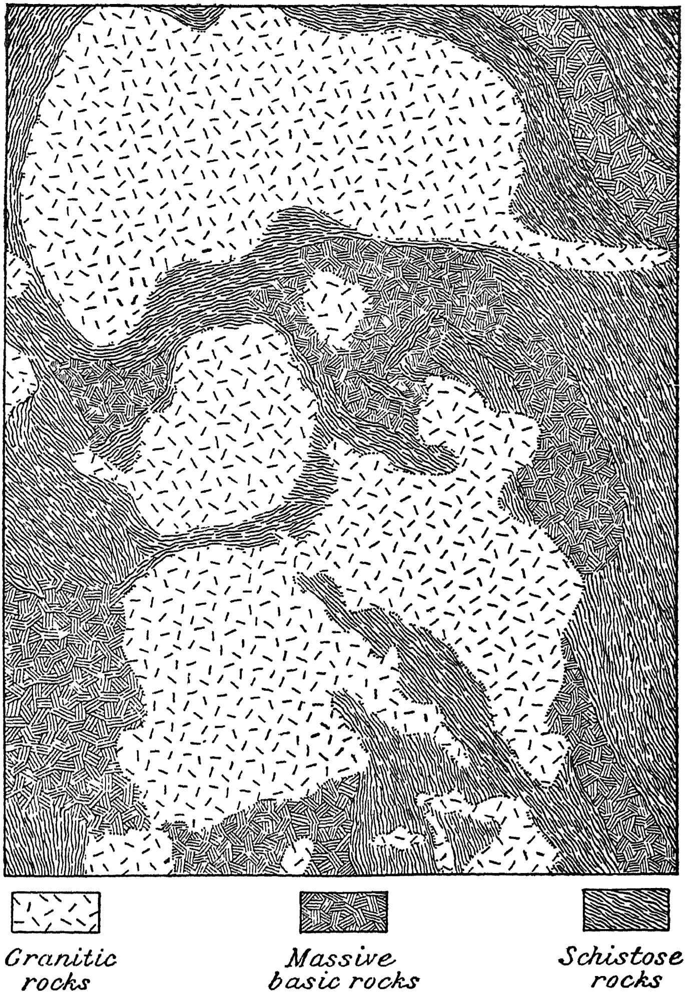

FIG. 41.—Plan of batholith in Bidwell Bar quadrangle, California (*divergent hachures*), (*broken lines* in country rocks). Scale, 1:490,000. (*After Bidwell Bar folio, No.* 43, *U. S. Geol Survey*, 1898.)

[1] See also B. K. Emerson, Mon. 29, U.S. Geol. Survey, 1898, Plates 25, 28, 31, 32, 34; J. C. Branner, Santa Cruz folio, U.S. Geol. Survey, 1909, map and sections; S. J. Schofield, Mem. 76, Geol. Survey Canada, 1915, p. 79; E. Kaiser on the Granitberg, Die Diamantenwüste Südwest Afrikas, Berlin, 1926, p. 276; W. N. Benson on the late Paleozoic batholith of New South Wales, Mem. Nat. Acad. Sciences, Washington, vol. 19, No. 1, 1926, map p. 38.

A large granitic mass without visible floor and crosscutting may be associated with other large granitic masses having contacts almost wholly concordant in strike with the country rocks. An example is seen in the Bidwell Bar quadrangle, California (Fig. 41). Lacking one characteristic of typical batholiths, the more concordant body on the north, in spite of its composition and great size, is not to be regarded offhand as of the subjacent class.[1]

Roof and Walls.—The form of the contact surface at the roof of a post-Archean batholith or stock tends toward that of a subcircular or elongated dome. However, the dome is usually diversified by

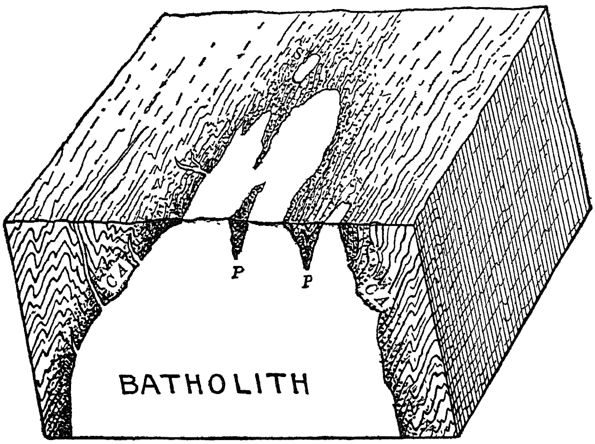

FIG. 42.—Diagram showing features of an ideal post-Archean batholith. *P*, roof pendants; *CA*, aureole of contact metamorphism in folded sediments; *S*, satellitic stock.

salients and re-entrants. The salients of country rock, with the shapes of inverted pyramids or downwardly directed wedges, are conveniently called "roof pendants" (Fig. 42).[2] Where erosion has progressed far enough, any direct evidence for connection of pendants with the rest of the roof is lost. That they were originally parts of the continuous roof may, as a rule, be inferred if the pendants are of large size and in ground plan have major axes faithfully parallel with the average strike of the rocks around the batholith. This criterion is likely to distinguish pendants from mere inclusions, that is, blocks that had been completely immersed in the molten magma. As shown in Chapter XII, large inclusions could not be supported by granite magma, even magma of high absolute viscosity, and the difference of

[1] In "Igneous Rocks and Their Origin" the concordance in strike was explained as a case of the development of peripheral schistosity by contact metamorphism. As pointed out by F. L. Ransome in a review, this is doubtless an error, the schistosity being reported older than the intrusion.

[2] R. A. Daly, Bull. Geol. Soc. America, vol. 17, 1906, p. 336.

density between solid and melt would normally compel some twisting of the inclusion out of its original direction of strike.

Illustrations abound throughout the batholithic zones of the American Cordilleras, as in California,[1] Idaho (Fig. 43), the State of Washington (Fig. 44), and British Columbia (Fig. 45).

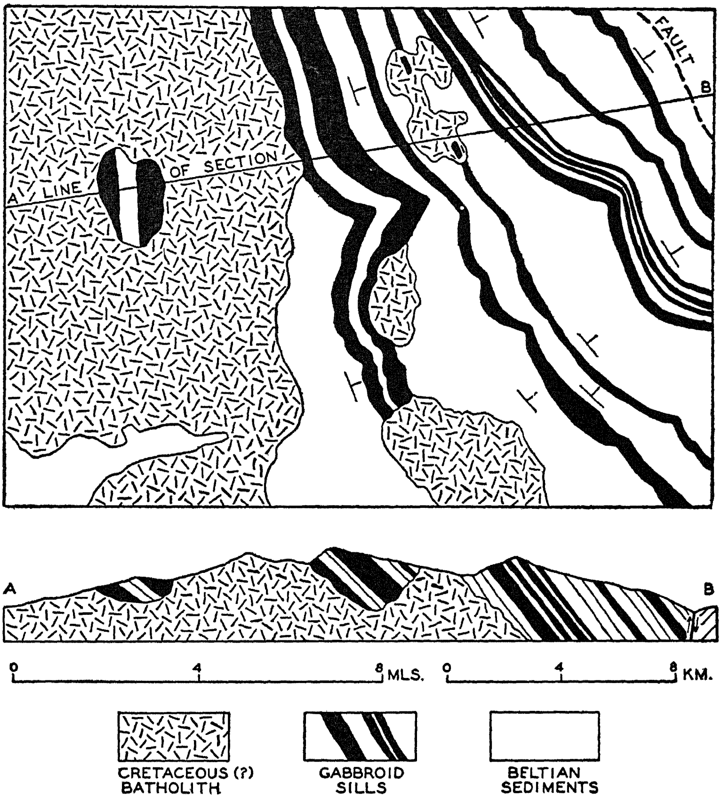

FIG. 43.—Map and section of a small fraction of the "Nelson" batholith, Idaho, illustrating cupola stocks, roof pendants, crosscutting and replacing character of a batholith. The thick gabbro sills are of late Beltian (late Pre-Cambrian) age. (*After V. R. D. Kirkham and E. W. Ellis, Bull.* 10, *Idaho Bur. Mines*, 1926.)

Again, the lines of contact of many batholiths are irregular for another reason—the presence of re-entrants into the roof rock. These upward projections of the intrusive mass may be called "cupolas" or "cupola stocks," using a second architectural analogy. Examples are shown in Figs. 43, 44, 48, 49, and 151.[2]

[1] A. Knopf, Prof. Paper 110, U.S. Geol. Survey, 1918, p. 62.

[2] B. S. Butler (Prof. Paper 111, U.S. Geol. Survey, 1920, p. 200) gives an instructive, highly graphic diagram illustrating in section cupolas, pendants, and their relation to ore genesis. He writes (p. 198): "The space occupied by the

As noted in the next chapter, some cupolas, when filled with magma, appear to have been open to the sky, so that the corresponding batholiths were locally roofless. This case is rare. Of course, a volcanic pipe, fed directly from a batholith, also breaks the continuity of the roof.

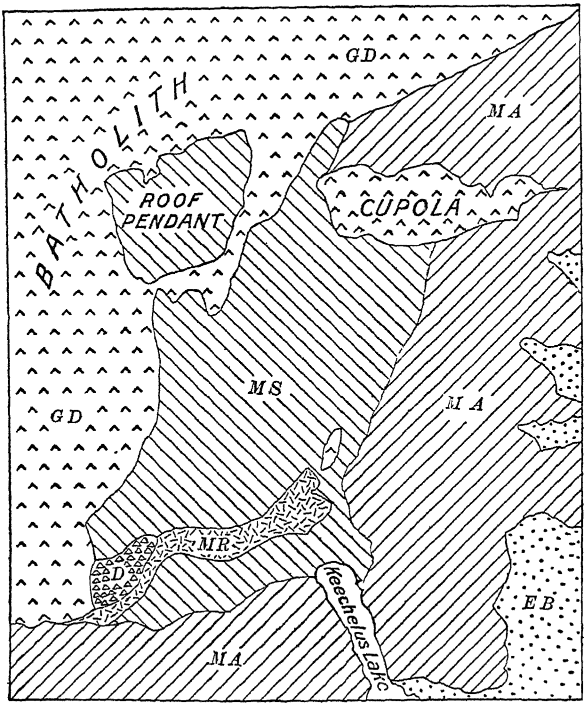

FIG. 44.—Map showing roof pendant in, and cupola stock satellitic from, the Snoqualmie batholith, State of Washington. *GD*, granodiorite, *D*, diorite; *MA*, andesite; *MR*, rhyolite; *MS*, slate, etc., *EB*, Teanaway basalt (Eocene). All formations except *EB* are of Miocene age. Scale, 1.210,000. (*After Snoqualmie folio, No.* 139, *U. S. Geol. Survey*, 1906.)

In general, a batholithic roof is marked off from the "walls" of the igneous body by a relatively sharp increase in the average dip of the surface of contact. Though the main walls, thus highly inclined, are broken by apophyses, they tend to be smooth. According to the accurate maps now published, the contacts of deeply eroded stocks and batholiths are generally represented with flowing lines—another

igneous material constituting the stocks was probably gained in large part by a pushing aside and doming of the earlier rocks." Yet the structure shown in the section quite clearly forbids that interpretation. If the section is in principle correctly drawn, we are practically compelled to assume that the magma was emplaced by stoping or else by the sinking of a solid floor beneath the visible granitic rock.

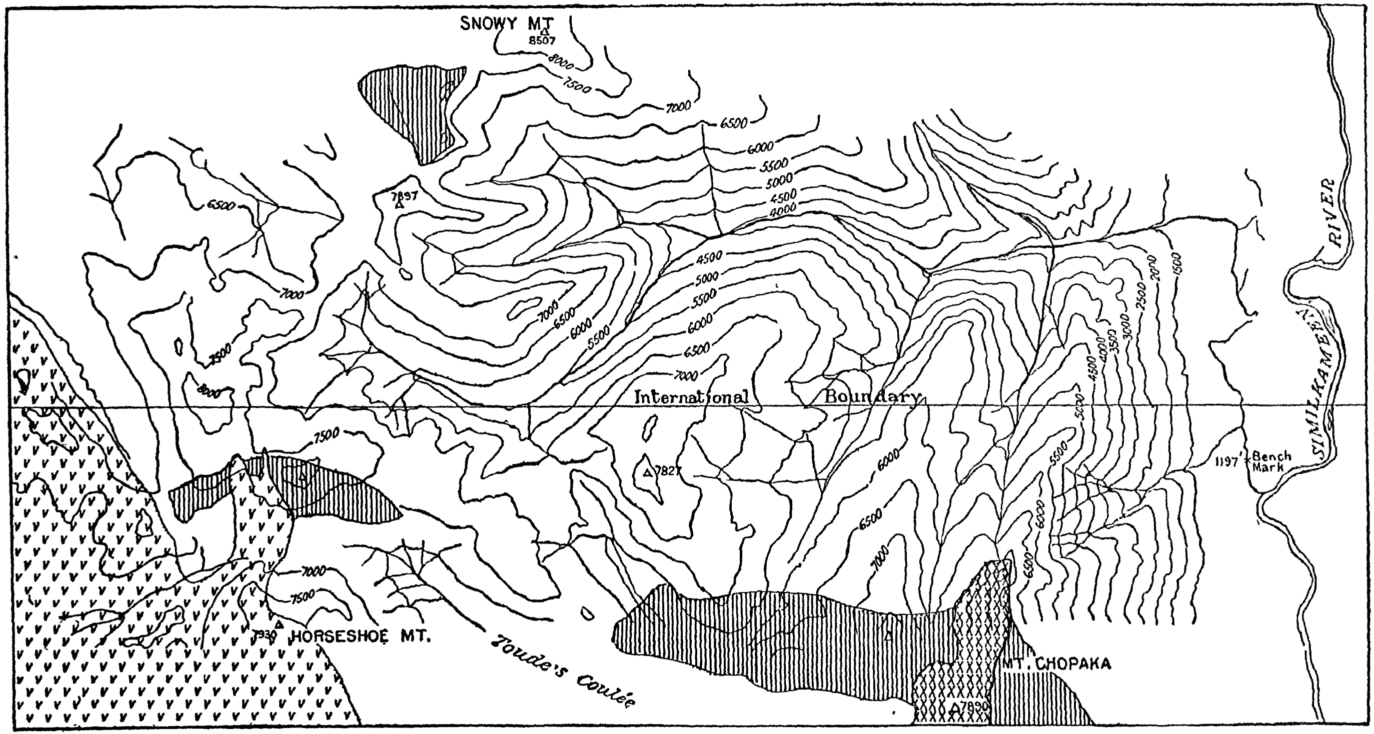

FIG. 45.—Roof pendants in the Similkameen granodiorite batholith (*blank*), British Columbia-United States boundary. *Inverted carets*, Cathedral granite batholith; *vertical lining*, schists of roof pendants; *crosses*, gabbro and dunite of pendant. Scale, 1:120,000; contours in feet. (*R. A. Daly*, *Mem.* 38, *Geol. Survey Canada*, 1912, *p.* 430.)

fact to be explained. Illustrations are given in Figs. 39, 40, 43, 45, 48, and 49.

Not many estimates of the thicknesses of batholithic roofs are in hand. Some are given in Table 22.

TABLE 22

Authority	Region	Estimated thickness of roof, meters
H. G. Backlund (Geol. Mag., vol. 63, 1927, p 412)..................	Andes, South Mendoza	400–1000
G. Steinmann (Geol. Rundschau, vol. 1, 1910, p. 22)..............	North Chili, Remolinos	1000–2000
G. Steinmann (Geol. Rundschau, vol. 1, 1910, p. 22).................	North Chili, Carrisal	4000–6000
G. Steinmann (Geol. Rundschau, vol. 1, 1910, p. 22).................	Peru	3000–4000
O. H. Erdmansdörffer (*ibid.*)... .	Brocken ("laccolith")	600–2000
K. Dalmer (Zeit. f. prakt. Geologie, vol. 8, 1900, p. 287).............	Erzgebirge	6000 (?)
W. Salomon................. ..	Adamello, Tyrol	*ca.* 1500
W. C. Brögger (Die Eruptivgesteine des Kristianiagebietes, vol. 2, 1895, p. 144).	Drammen, Norway ("laccolith")	*ca.* 1600
J. Barrell (Prof. paper 57, U. S. Geol. Survey, 1907, p. 166).........	Boulder, Idaho	*ca.* 670
G. F. Loughlin (Prof. paper 107, U. S. Geol. Survey, 1919, p. 65).......	Tintic dist., Utah	1000 or less
G. O. Smith (Snoqualmie folio, U. S. Geol. Survey, 1906, p. 12).	Snoqualmie district, State of Washington	1200
T. W. Gevers (Trans. Geol. Soc. South Africa, vol. 35, 1932, p. 92).	Erongo, Southwest Africa	600

Harker remarks that "the minimum depth of cover under which large plutonic rock-bodies may be intruded is, perhaps, often exaggerated."[1] In any case, the relative thinness of cover is not easy to understand on any theory of the mechanics of intrusion, especially so if the greater batholiths be assumed to be pure injections (see page 281).

Downward Enlargement.—Thus, to visible depths the slope of the interface of contact is prevailingly outward, away from the intrusive. Although in many cases the rate of this downward enlargement of batholiths is known to fall off rapidly at comparatively shallow depths, most students of these bodies assume some enlargement for them to depths of a few kilometers—an extrapolation which can hardly be called wildly speculative (see Figs. 43, 50, 54, 102, and 103).

[1] A. Harker, The Natural History of Igneous Rocks, New York, 1909, p. 86.

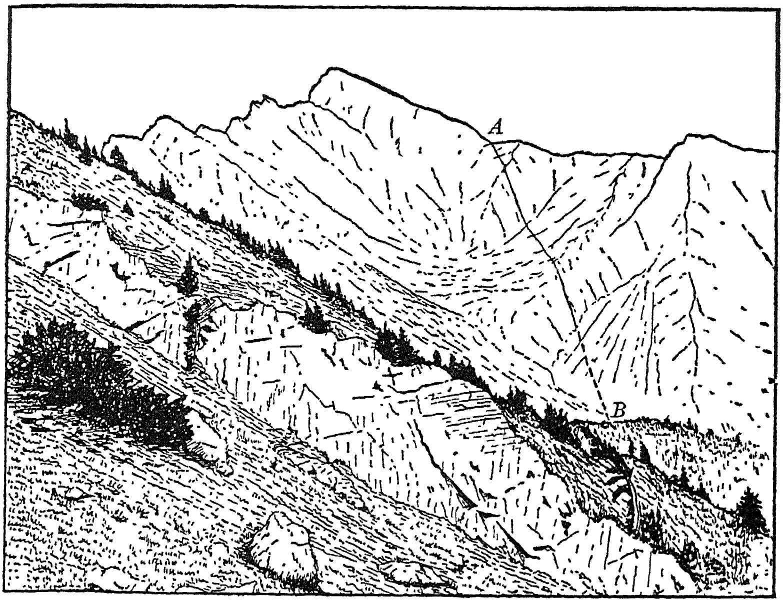

FIG. 46.—Plunging contact (*AB*) at south side of granodiorite stock (left) cutting Cretaceous sediments (right) at Castle Peak, British Columbia. The vertical distance between *A* and *B* levels is 240 meters. Traced from a photograph. (*R. A. Daly, Mem.* 38, *Geol. Survey Canada*, 1912, *p.* 498.)

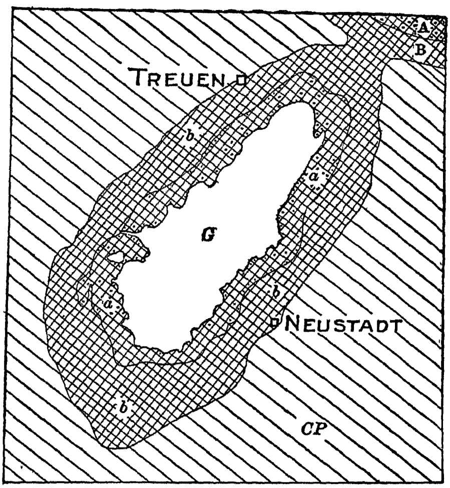

FIG. 47.—Map showing partial unroofing of a large granite stock in Saxony. *G*, granite; *CP*, Cambrian and older argillite and phyllite; *a*, inner metamorphic aureole; *b*, outer metamorphic aureole; *A*, inner aureole of Kirchberg-Schneeberg granite batholith; *B*, outer aureole of the same. The great width of *a* and *b* suggests that much of the roof of the stock still remains. Scale, 1:275,000. (*After Geol. Spezialkarte des Kön. Sachsens—Treuen and neighboring Sektionen.*)

Direct observation of downward enlargement in the natural sections displayed along deep valleys is exemplified in Fig. 46, illustrating some of the best exposures of the kind yet recorded.

Direct determination of downward enlargement during mining operations was accomplished at Marysville, Montana (Fig. 104) and at Tintic, Utah (Fig. 101).

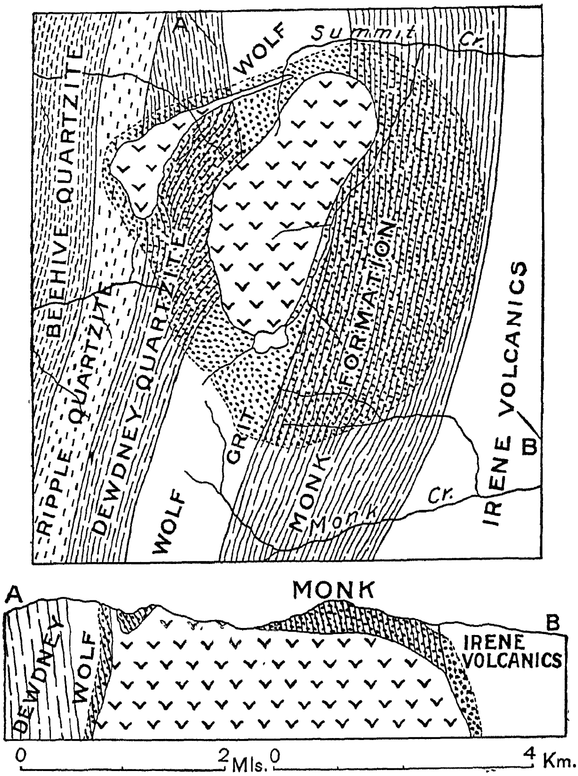

FIG. 48.—Map and section showing crosscutting character and downward enlargement of a granite stock (*inverted carets*) in the Selkirk Mountains, near the forty-ninth parallel of latitude. The broad aureole of contact metamorphism and shattering in the nearly vertical strata is shown with dots. (*R. A. Daly, Mem.* 38, *Geol. Survey Canada*, 1912, *p.* 299.)

More indirect, yet trustworthy, evidence is found in the aureoles of contact metamorphism. For the normal exposures of batholiths and stocks, such metamorphism tends to be at maximum within the roof rock. Hence an aureole of unusual width suggests the horizontal extension of the intrusive body beyond its exposed limit (Fig. 47). This indication becomes still more assured where satellitic stocks (cupolas) emerge within the broad aureole. Examples are shown in Figs. 48 and 49. Other good cases are described by Smith and Calkins

in the State of Washington, and by Kennedy at Traversella, Piedmont, Italy.[1]

Even without exposure by erosion, the existence of batholithic masses has been inferred where considerable areas of rocks show

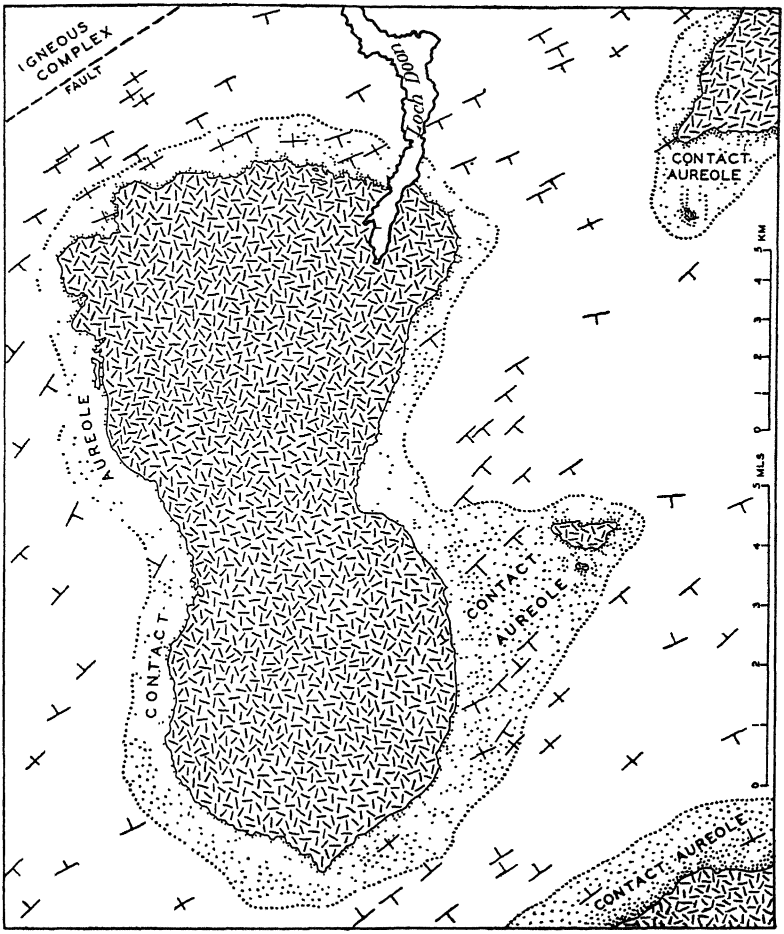

FIG. 49.—Map of a batholithic mass in southern Scotland, illustrating widening of the contact aureole where the roof is locally preserved, the crosscutting relation; and satellitic stocks. The intensity of the contact metamorphism varies according to the spacing of the dots in the stipple pattern. Tonalite and granite (*hachures*), of Old Red Sandstone age, cut closely folded Ordovician and Silurian sediments (left *blank*). See Fig. 115. (*Taken from the Carrick sheet, Geol. Survey Scotland.*)

intense contact metamorphism. Such deductions have been made by G. F. Loughlin in Utah, S. J. Schofield in British Columbia, T. A.

[1] G. O. Smith and F. C. Calkins, Snoqualmie folio, U.S. Geol. Survey, 1906, p. 10; there the aureole is 5 kilometers wide. W. Q. Kennedy, Bull. Suisse de Minér. et Petr., vol. 11, 1931, p. 96.

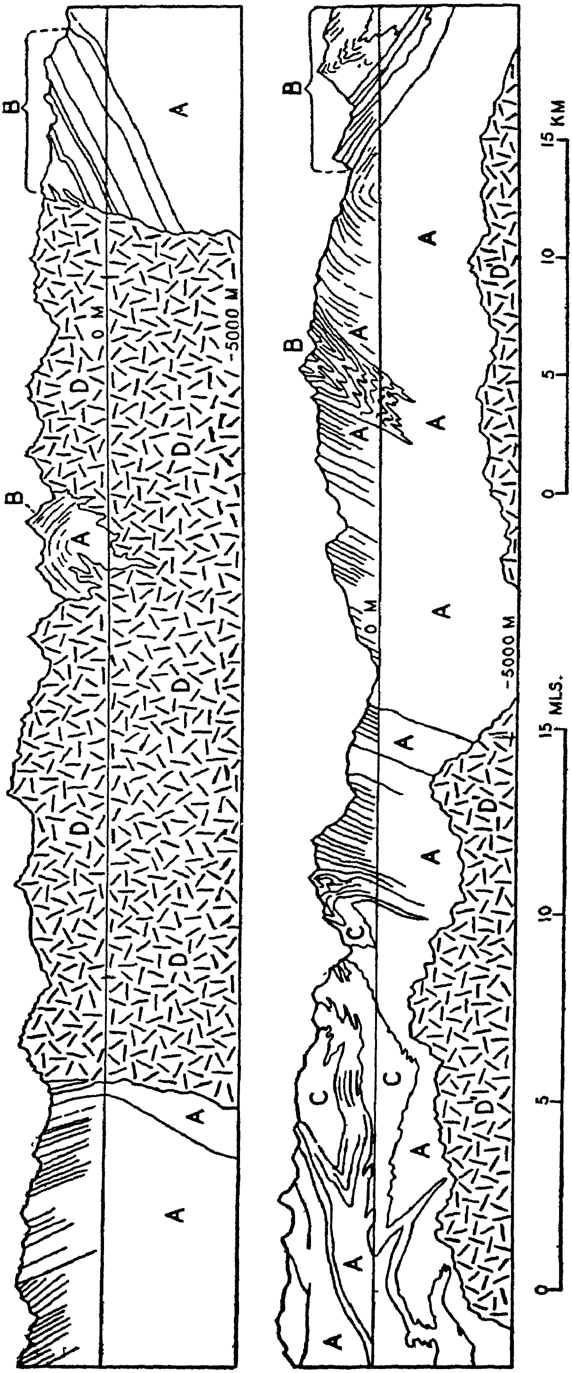

FIG. 50.—Upper section through the batholithic Adamello mass, Eastern Alps. Lower section, 50 kilometers to the westward, shows on the right the assumed westward prolongation of the same mass underground; on the left the analogous eastward prolongation of the Bergell (Bregaglia) batholith D, granite; C, ophiolite; B, Verrucano and Lower Mesozoic; A, "Old" crystalline rocks. (*After A. Heim, Geologie der Schweiz, vol. 2, Leipzig*, 1922, *Plate* 35.)

Jaggar and C. Palache in Arizona. In a similar way Bastin infers the presence of a batholith in moderate depth merely because of the local abundance of pegmatite dikes in the State of Maine.[1]

By combining such varied evidences, many geologists have not hesitated to publish sections showing increase of width for batholiths with increase of depth. Thus Heim pictures the Bergell (Val Bregaglia) and Adamello masses of the Alps (Fig. 50); Berkey and Morris, the Mongolian batholith; Kirkham and Ellis, the "Nelson" batholith of Idaho and British Columbia (Fig. 43); Schofield, the big Coast Range batholith of British Columbia and Alaska. Even Steinmann, who explained the Andean granodiorite as injected chonolithically during the mountain building and hence initially provided with a solid floor, had no doubt about the subterranean merging of the visible bodies of granodiorite into a vast, single mass.[2]

Legitimate extrapolation from sections at and near the earth's surface should, of course, take account of the numerous observed cases where the outward dip of the contact surface rapidly increases with depth. This fact strongly suggests a limit to the downward enlargement of most batholiths at least.

Moreover, the general rule of downward enlargement by no means excludes cases where the contact surfaces locally dip toward the intrusives. Some of these exceptions are doubtless to be explained by late, more or less horizontal displacements of the respective batholithic magmas after their rise from depth had been nearly or quite completed.

In this connection it is worth while to note the views of Barrell, one of the ablest students of the batholithic problem. Concerning subjacent bodies he wrote:

> The first step in observation and inference is from the nature of the margins. These in places show broad, flat or domal, or irregular roofs; in other places, contacts plunging steeply for thousands of feet. The general character, however, is a broadening in depth. Inference from the nature of the outcrops can not safely lead us very far, but it does show no evidence of a bottom, no narrowing into pipes or laccolithic form. The doming of the roof would result from the hydrostatics of the magma, without need of any floor. Being lighter than the solid rock around it, the batholith must perforce exert an upward pressure, and a pressure greater in proportion to the thinness of the cover.

[1] E. S. Bastin, Jour. Geol., vol. 18, 1910, p. 318.

[2] A. Heim, Geologie der Schweiz, Leipzig, vol. 2, 1922, Pl. 35; *cf.* Pl. 26 and p. 61. C. P. Berkey and F. K. Morris, Geology of Mongolia, New York, 1927 (thirteen sections, many showing roof pendants). V. R. D. Kirkham and E. W. Ellis, Bull. 10, Idaho Bur. Mines and Geol., 1926, Pl. 3. S. J. Schofield, Econ. Geol., vol. 21, 1926, p. 277. G. Steinmann, Geol. Rundschau, vol. 1, 1910 (text and sections), pp. 23, 27.

The next step downward is taken by noting the relation of cupolas to the main body. The roof is seen to be irregular, and beyond the margin satellitic stocks break up and are intersected by the erosion surface. Erosion to a greater depth would join these to the parent body, and show at farther distances a new set of satellitic stocks. The location of these latter can be recognized in places by centers of outlying metamorphism or centers of converging dikes. . . . The dikes, to those who seek their meaning, look inward to a hidden igneous body, like the statues of the Alhambra legend whose eyes focussed on the spot of buried treasure.[1]

A Negative Characteristic of Post-Archean Batholiths.—A related fact: we have no direct evidence that the intracrustal space occupied by a typical batholith was gained principally through a laccolithic or bysmalithic lifting of the roof, or through a thrusting-aside or pulling-apart of the walls, dikewise, or through any combination of these two kinds of crustal displacement. Roofs are not sufficiently domed to warrant the laccolithic hypothesis. The circumferential faults demanded by the bysmalithic hypothesis are conspicuously absent.[2] Field observation gives no good ground for assuming the dike hypothesis as explanatory of the upper part of any batholith, however the case may be with the lower part. The actual method of space winning and intrusion at invisible depths is a matter for speculation and thus reserved for subsequent chapters (XI and XII). Here we are concerned primarily only with the roof region of the batholith. For this fraction of the whole batholithic space, the country rocks appear to have been replaced by the magma, though a fraction of this fraction may, in some instances, be due to moderate doming of the roof.

How this replacement of the roof rocks was accomplished is, perhaps, not so obvious as the fact itself, but by the logical process of exclusion we can hardly fail to reach a conclusion: the replaced rocks have sunk away, their space being taken by the rising magma. Whether these rocks were correspondingly bent down or faulted down (in each case retaining some solid connection with the earth's crust), or stoped down piecemeal or *en bloc*, is an important question, but again theoretical and to be deferred in discussion (see Chapter XII). Meantime we dwell upon the more objective fact.

Among the crowd of illustrations of replacement of roof and wall rocks may be mentioned the Marysville stock (Figs. 103 and 104); the wonderfully exposed stock at Castle Peak, British Columbia and

[1] J. Barrell, Amer. Jour. Science, vol. 1, 1921, pp. 6–7 (published posthumously). Barrell regarded the isostatic balance of mountain ranges as partly due to the great volumes of such downwardly enlarging batholiths.

[2] H. Cloos (Der Erongo, Beitr. z. Erforsch. d. deut. Schutzgebiete, Heft 17, 1919, p. 199) showed how the "bysmalithic" mechanism quite fails to explain the emplacement of the various stocks of the Erongo granite, Southwest Africa.

State of Washington (Figs. 40, 51); the composite stock at Ascutney Mountain, Vermont (Fig. 96); the stocks satellitic to the Bayonne batholith, British Columbia (Fig. 48); many stocks and small batholiths in Brittany (Fig. 52) and in the Pyrenees (Fig. 39).

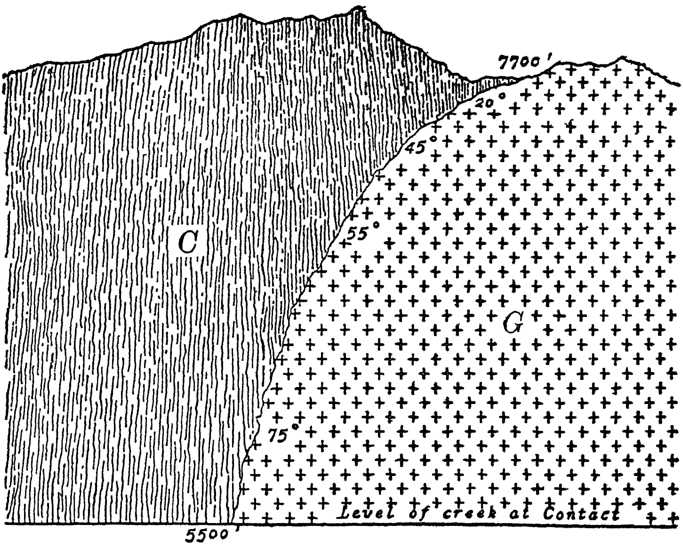

FIG. 51.—Canyon-wall section at north of Castle Peak stock, British Columbia; from a field sketch. *G*, granodiorite; *C*, Cretaceous argillite. Elevations in feet; dips in degrees. (*Mem.* 38, *Geol. Survey Canada*, 1912, *p.* 499.)

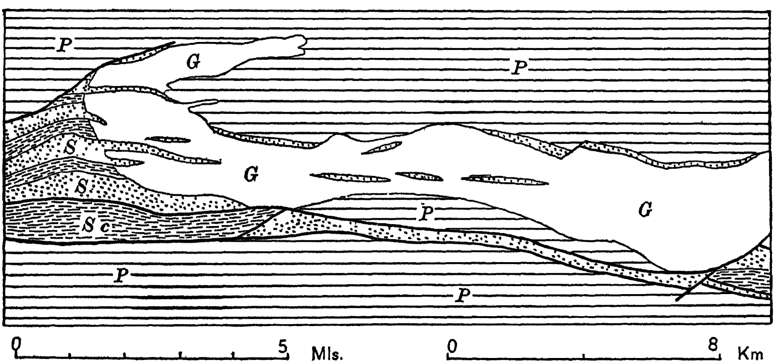

FIG. 52.—Map showing replacement of sediments by a granite batholith (*G*) in Brittany. *Sc*, Silurian and Devonian slates; *S*, Silurian sandstones; *P*, St. Lô phyllites. Note the preservation of strike in the sandstones. (*After C. Barrois*, *Annales soc. géol. du Nord*, *vol.* 21, 1893, *p.* 240.)

Sederholm and Salomon both agree that in many instances the replacement hypothesis gives the only possible explanation of the larger granitic massifs.[1]

[1] J. J. Sederholm, Geol. Rundschau, vol. 4, 1913, p. 175. W. Salomon, *ibid.*, vol. 1, 1910, p. 13.

According to Knopf, field evidence lends strong support to the contention "that batholithic invasion is not accompanied by disturbance of the tectonic axes of the invaded rocks."[1]

In general, the final stage of batholithic emplacement represents a relatively quiet process, unaccompanied by such colossal movements of the surrounding rocks as would be required to form the corresponding space by the laccolithic, bysmalithic, or chonolithic mode of intrusion. Such appears to be the ineluctable conclusion of common sense, reacting directly on field observation. In summary, at the highest levels reached, the typical subjacent body seems to have been emplaced by a kind of corrosion of the earth's crust on a grand scale.

Chemical Composition.—The larger subjacent masses are usually granitic, quartz-monzonitic, or granodioritic, though batholiths of quartz diorite and syenite are known. It is an open question whether any other plutonic type composes a true batholith, that is, a subjacent body more than 100 square kilometers in exposed area. The large intrusions of alkaline rock near Julianehaab, Greenland, are called batholiths by Ussing; yet certain of their structural relations as well as the character of their magmatic differentiation indicate a chonolithic, lopolithic, or laccolithic mode of intrusion.[2]

Stocks have a wider range of composition, including the species listed above and also gabbro, norite, quartz gabbro, diorite, nephelite syenite, etc., or their porphyritic equivalents.

As already noted, even very extensively exposed masses of granite are not batholithic; the Basement Complexes are strongly charged with laccoliths, phacoliths, and perhaps also lopoliths of individual areas rivaling the batholiths. Moreover, the impressive volume of granite constituting much of the Bushveld Igneous Complex seems to be part of a composite lava flow of unexampled dimensions, though the feeder of the gigantic flow may have cross section and relations much like those of a typical batholith.[3]

Classification

Simple stocks are composed of material intruded during one period of irruption. Types are illustrated by Figs. 40, 47, 102, and 105.

On the analogy of multiple dikes, a multiple stock may be conceived, namely, one which is composed of uniform material demon-

[1] A. Knopf, Prof. Paper 110, U.S. Geol. Survey, 1918, p. 63.

[2] N. V. Ussing, Medd. om Grönland, vol. 38, 1911, pp. 38, 49, 50, 68, 251–255, 290, and Pl. 6.

[3] See Fig. 90 and compare R. A. Daly, Bull. Geol. Soc. America, vol. 39, 1928, p. 767.

strably intruded at two or more distinct stages of one eruptive period. Apparently no example is on record.

A composite stock is composed of materials demonstrably intruded at two or more distinct stages of one eruptive period, the magmas of the different intrusions having different compositions (see Fig. 96).

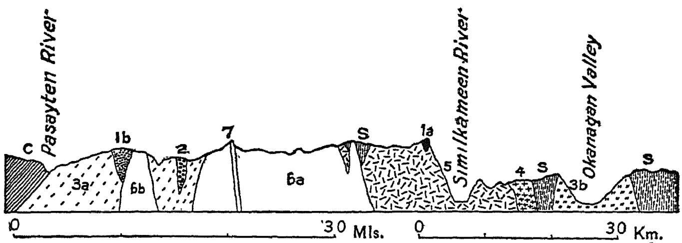

FIG 53 —Section of Okanagan composite batholith at the 49th Parallel. *S*, Paleozoic schist, limestone, quartzite, etc.; *C*, Cretaceous sandstone and volcanic breccia; *1a*, Chopaka peridotite; *1b*, Basic complex (gabbro, hornblendite, etc.); *2*, Ashnola gabbro; *3a*, Remmel granodiorite (gneissic); *3b*, Osoyoos granodiorite (gneissic); *4*, Kruger nephelite syenite and malignite; *5*, Similkameen granodiorite; *6a*, Cathedral granite, older phase; *6b*, Park granite, *7*, Cathedral granite, younger phase. The igneous rocks are numbered in the order of intrusion. Vertical exaggeration of about 5 to 1. (*R. A. Daly*, *Mem.* 38, *Geol. Survey Canada*, 1912, *p.* 426.)

In corresponding fashion, simple and composite batholiths may be distinguished. No multiple batholith has been described and there is reason to doubt that one shall ever be discovered. During the long time taken to crystallize a considerable part of a batholith, the forces leading to the differentiation of the residual liquid can hardly fail to produce magma contrasting chemically with the older, already solidi-

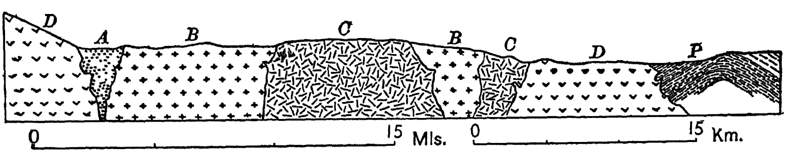

FIG. 54.—Section of the composite batholith of New England, New South Wales. *P*, Permo-Carboniferous sediments; *A*, Dark porphyries, *B*, "Blue granite"; *C*, sphene-granite porphyry; *D*, "acid granite." The rocks are named in the order of intrusion. Scale approximate. (*After E. C. Andrews*, *Rec. Geol. Survey New South Wales*, *vol.* 8, *part* 2, 1905, *Fig.* 7.)

fied phase. In general, therefore, renewed intrusion during a single petrogenetic cycle should give a composite, not a multiple, batholith.

The greatest exposed post-Cambrian batholith is doubtless that forming the greater part of the Coast Range of British Columbia and Alaska, a body nearly 2000 kilometers long, reaching a maximum width of about 200 kilometers (Fig. 36). A composite outlier of the Coast Range batholith proper occurs in the Okanagan region of the

State of Washington and British Columbia (Fig. 53).[1] Nearly all the larger plutonic masses of the North American Cordillera seem to be composite. The composite Patagonian batholith (Fig. 38) measures 1100 by 110 kilometers. Another fine illustration is that in New South Wales (Fig. 54).[2]

[1] R. A. Daly, Bull. Geol. Soc. America, vol. 17, 1906, p. 329.
[2] *Cf.* Ida A. Brown, Proc. Linn. Soc. New South Wales, vol. 53, 1928, p 151.

CHAPTER VIII

EXTRUSIVE BODIES

A classification of volcanic masses and the associated topographic forms may next be reviewed. Founded primarily on field observations, the scheme is neither complete nor wholly genetic. It serves, however, to exhibit leading facts.

The volcanic bodies fall into three principal groups, corresponding to as many different modes of extrusion. Two of the groups, respectively formed by "fissure" or "linear" eruption and by "central" eruption are regularly named and discussed in modern textbooks. The third, less abundant in nature, includes the products of what is here called "deroofing" or "areal" eruption.[1] Although transitional into one another, the recognition of the three pure types is none the less helpful in forming a basis for volcanic theory.

I. Fissure (Plateau, Linear, Labial) Eruptions; Taphroliths

The simplest mode of extrusion characterizes the greatest basaltic fields. As a rule, the lavas have there issued quietly, without explosion of violence sufficient to form dominant layers of tuff or other pyroclastic material. However, occasional ash beds locally interrupting the lava flows represent temporary eruption, sometimes including that of the familiar central type. The eruption at the Icelandic Skaptar Jökull fissure during 1783, the most imposing historic example, illustrated this subordinate part of pyroclastic deposits in basaltic plateaus.

Table 33, page 264, lists important fissure eruptions, called "linear eruptions" by von Wolff and "labial eruptions" by Supan. Those of Tertiary date are generally little deformed and merit the common name plateau basalts. The fields celebrated for their extent are those of India (Fig. 55), South Africa, Northern Argentina, Brazil, Uruguay, Patagonia, Siberia, and the Northwestern United States. Even the visible parts of the North Atlantic plateau basalts are considerable, as shown by Thoroddsen's table:

[1] H. Reck (Deutsche Island-Forschung, Breslau, 1930, p. 30) doubts that the roofs of magmatic chambers have ever been broken open so as to expose large areas of the magma to the air. Contrary to his German colleagues, he prefers to make "areal eruption" describe the formation of non-alined clusters of ordinary lava rents or gas vents (maars).

	Estimated Areas, Square Kilometers
Scotland and Ireland	10,000
Faroe Islands	1,325
Iceland	104,785
East coast of Greenland	20,000+

The total area may exceed 500,000 square kilometers. If so, the Thulean basalts, together with those of South America, the Northwestern United States, and the Deccan, would give a grand total of

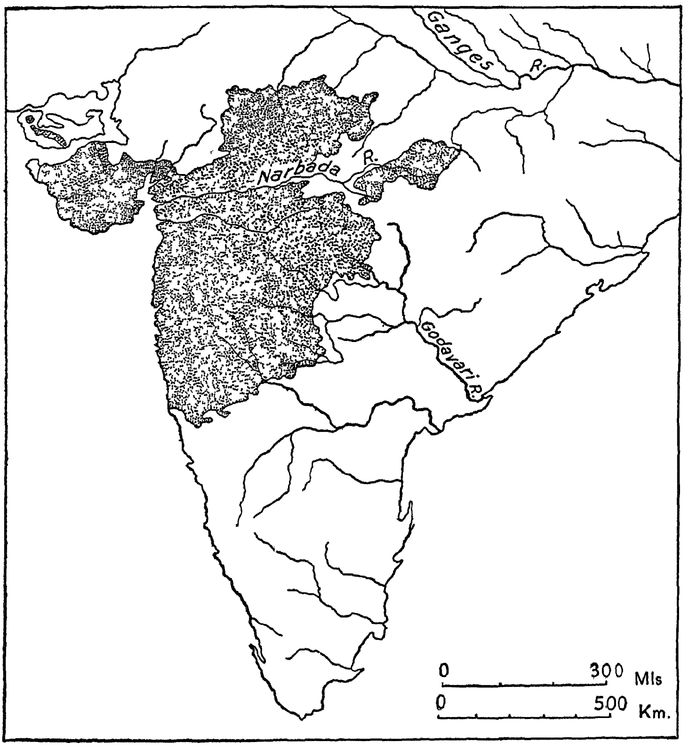

FIG. 55.—Map showing distribution of the Deccan traps (*dotted*).

2,500,000 square kilometers, or nearly one-half of the area estimated by von Tillo to be covered by all the "young" volcanic masses of the continents and islands.

Observed thicknesses for the plateau basalts reach high figures. The maximum proved for the Teanaway basalt (Eocene) in the State of Washington is 1830 meters. That for the Oregon field is of the same order. The Yakima basalt (Miocene) is more—perhaps much more—than 600 meters in thickness at the Yakima River canyon. A. Geikie estimated the maximum thickness of the Iceland basalts at

3000 meters. That of the plateau basalt in western Greenland is more than 1200 meters. The Deccan traps are locally more than 1800 meters thick.

Few individual flows exceed 100 meters in thickness. In the United States the average thickness is probably less than 15 meters, which is about the average for the Mull flows and also for fifty-one Deccan flows.[1] Thoroddsen stated that the Icelandic flows range from 5 to 10 meters. The Basutoland flows range from less than 1 meter to 50 meters.[1]

Where, however, the eruption takes place in a valley, the lava may attain much greater depth. Lee mapped a remarkable case at

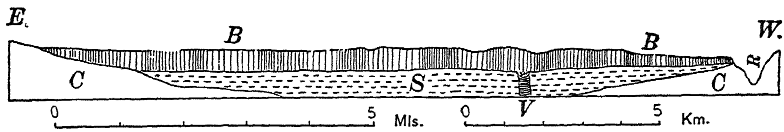

FIG. 56.—Section of great fissure eruption in Williams Canyon, Arizona. *C*, crystalline rocks; *S*, sand and gravel; *B*, massive flow of basalt; *V*, vent of the flow, 120 meters in diameter. (*After W. T. Lee, Bull.* 352, *U. S. Geol. Survey*, 1908, *p.* 54.)

Williams Canyon, Arizona, where the basalt covers an area 14 kilometers broad and 22 kilometers long, the thickness in the middle being about 240 meters. This flow has a well-exposed feeder with the unusual width of 120 meters (Fig. 56).[2]

Thoroddsen counted eighty-seven "recent" fissure flows of basalt in Iceland and gave lengths, areas, volumes, and surface slopes of some examples:

Flow	Length, kilometers	Area, square kilometers	Volume, cubic meters	Slope
Laki fissure (1783 eruption)	90	565	12,320,000,000	
Veidivatnahraun (prehistoric)..	150	1080	43,160,000,000	5′
Frambruni (prehistoric)... ...	110	465	23,250,000,000	30–41′
Eldgjá (about 930 A.D.) . ..	...	....	9,325,000,000	

He estimated the volume of the biggest liparitic flow of Iceland (Hrafntinnihraun) to be about 500,000,000 cubic meters and thus small when compared with the basaltic floods.[3]

[1] E. M. Anderson, Mull memoir, Geol. Survey Scotland, 1924, p. 102. L. L. Fermor, Rec. Geol. Survey India, vol. 58, 1925, p. 114.

[2] W. T. Lee, Bull. 352, U.S. Geol. Survey, 1908, p. 54.

[3] A convenient copy of Thoroddsen's map of Iceland, showing the distribution of the early Tertiary and younger basalts, and also volcanoes of the central type, has been published by E. B. Bailey (Geol. Mag., vol. 6, 1919, p. 468).

The feeding dikes of some of the plateau flows are numerous (Fig. 57). The widths of few of these dikes surpass 50 meters and they average probably less than 10 meters. The narrowness is one of the direct evidences for the rapidity of these extrusions. If the magma remained stagnant many days or weeks, it would have necessarily solidified and sealed the fissures. The reopening would have had to await the removal of the congealed rock by explosion or refusion. Neither process seems to have been regularly at work in the fields of

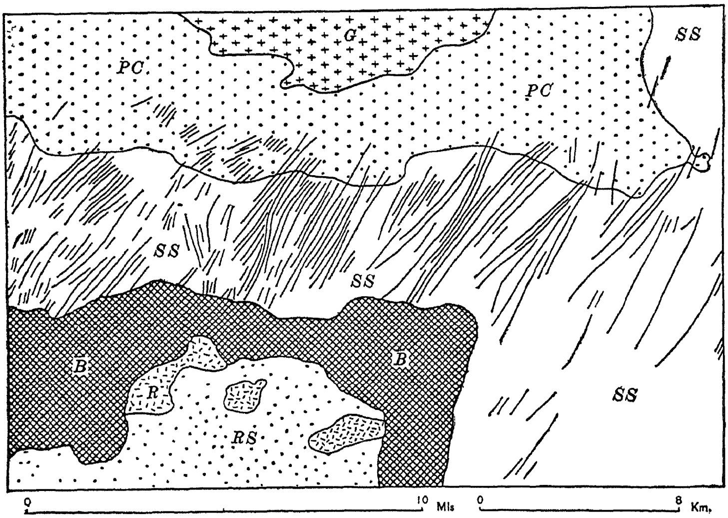

FIG. 57.—Map of dike feeders of Tertiary fissure eruptions near Mount Stuart, Washington. *PC*, pre-Tertiary complex (peridotite and greenstone); *G*, Mount Stuart granodiorite; *SS*, Eocene Swauk sandstone; *B*, Eocene basaltic fissure eruptions, their feeders shown by lines; *RS*, Eocene Roslyn sandstone and shale; *R*, Pliocene (?) rhyolite. (*After Mt. Stuart folio*, *No.* 106, *U. S. Geol. Survey*, 1904.)

plateau basalts. Thus fissure eruption is best regarded as a sudden act.

On the other hand, feeding dikes are extremely rare along the grand cliffs of Basutoland, as they are also in a few other fields. In part this fact finds explanation if it be assumed that the lavas actually issued at points or along limited sections of the fissures. Compare Garde's sketch of an analogous instance (Fig. 116) and also the Laki case itself. Exposure of the feeders would have to be a relatively rare chance.[1]

[1] From the rarity of dike feeders in the British province of Tertiary basalts, H. H. Thomas (Ardnamurchan memoir, Geol. Survey Scotland, 1930, p. 53) has come to question the reference of these Thulean piles of lava to the class of fissure eruptions. "Thus Judd's contention that the plateau basalts originated from a series of central volcanoes of Hawaiian type cannot be dismissed as untenable."

Among the fissure eruptions, petrographic types other than basalt are represented. The rhyolite of Corsica appears to have welled up through many fissures rather than through pipes. According to Gregory, trachyte, andesite, and basalt are all products of this mode of extrusion along the Great Rift of Africa.[1] Yet for the world as a whole, basalt probably constitutes as much as 90 or 95 per cent of the total volume of fissure eruptives.

Sederholm concluded that the Rapakivi granite in southern Finland is a thick flow, poured out on the surface of a fault trough or graben, the liquid rising along one or more of the faults concerned. To such

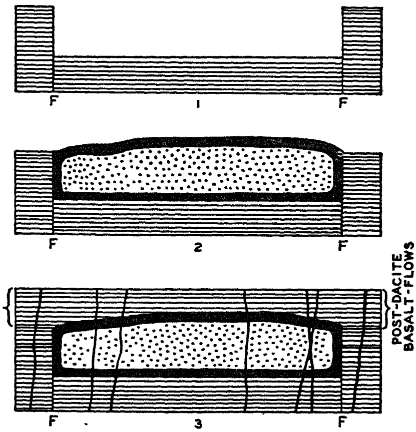

FIG. 58.—Development of a dacitic taphrolith in Iceland. *1*, Subsidence of a tract of basaltic flows along faults (*F*). *2*, Extrusion of dacite lava (taphrolith), the black border representing glassy and spherulitic facies. *3*, Submergence of the taphrolith beneath succeeding flows of basalt. Later diking by dolerite. Length of taphrolith in section is 900 meters. (*L. Hawkes, Quart. Jour. Geol. Soc. London, vol.* 80, 1924, *p.* 555.)

an extrusive mass he gave the name *taphrolith* (Greek *taphros*, a trench).[2] A smaller example, of Tertiary date, has been found in Iceland (Fig. 58).[3]

II. Extrusion by Deroofing ("Areal" Eruption)

The covers of most exposed batholiths must have had moderate initial thicknesses.[4] Notwithstanding the wide spans of their roofs, and also in spite of the fact that average roof rock was denser than the salic magma, most batholiths appear to have kept their roofs intact during the respective magmatic periods. In fact, few textbooks men-

[1] J. W. Gregory, The Great Rift Valley, London, 1896, p. 235.

[2] J. J. Sederholm, Tschermaks Min. u. Petr. Mitt., vol. 12, sep., 1891, p. 30.

[3] L. Hawkes, Quart. Jour. Geol. Soc. London, vol. 70, 1924, p. 555.

[4] Compare Table 22 of the last chapter.

tion the possibility of partial foundering. Nevertheless, indications are not wanting that some subjacent masses, when molten, were bared to the sky over areas much more extensive than those represented at ordinary volcanic vents.

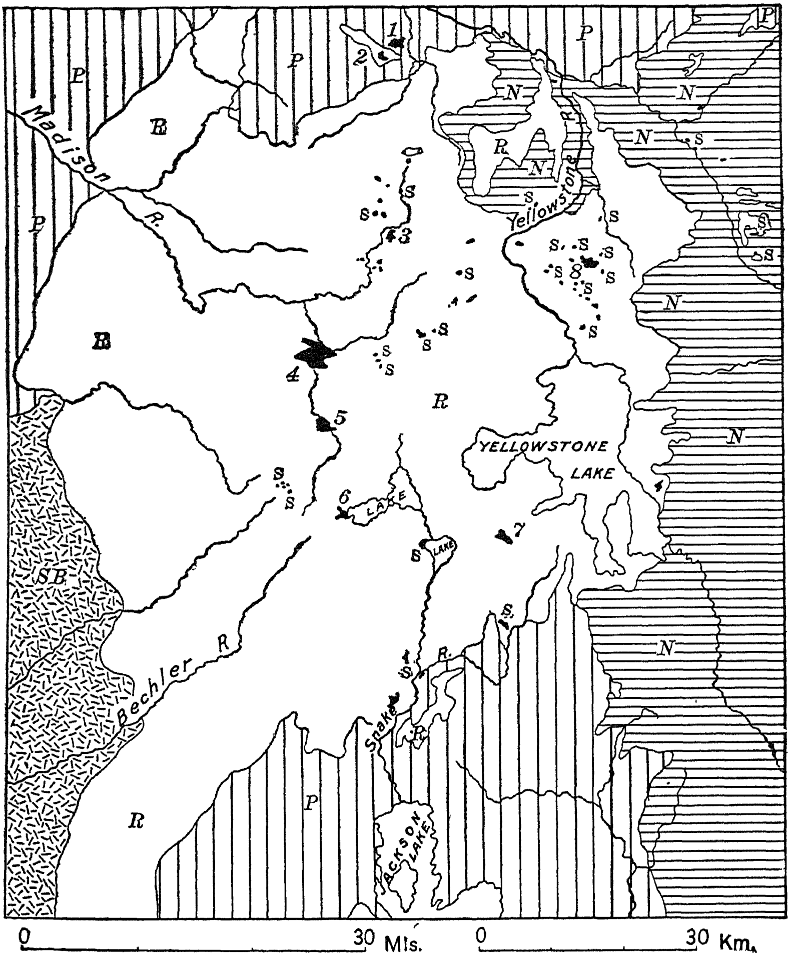

FIG. 59.—Map of the Yellowstone Park, showing the unexampled profusion of hot springs (*S*) and geyser basins. *P*, pre-Tertiary formations; *N*, pre-rhyolite, Neocene volcanic breccias; *R*, rhyolite (Pliocene or Miocene); *SB*, Snake River basalt (Pliocene); *black spots*, sinter deposits; *1*, Mammoth Hot Springs; *2*, Terrace Mountain; *3*, Norris Geyser Basin; *4*, Lower Geyser Basin; *5*, Upper Geyser Basin; *6*, Shoshone Geyser Basin; *7*, Heart Lake Geyser Basin; *8*, Hot Spring Basin. (*From Yellowstone National Park folio, No.* 30, *U. S. Geol. Survey*, 1896.)

Among such speculative cases the writer has emphasized the rhyolite of the Yellowstone National Park. Though the rhyolite forms ordinary superposed flows around the periphery of the plateau,

it is decidedly massive and perhaps monolithic in the central area, where, for example, the Madison and Bechler Canyons with depths of 500 meters are entirely walled with this lava.[1] These walls should be studied with the question in mind as to whether the central area coincides with a broad cicatrix in the roof of a batholith—a locus of foundering (see Figs. 59, 60). The active geysers are also centrally placed on the plateau. They and the older, now extinct, geysers have been squandering the magmatic heat for many tens of thousands of years, perhaps ever since the rhyolite was erupted. The eruption

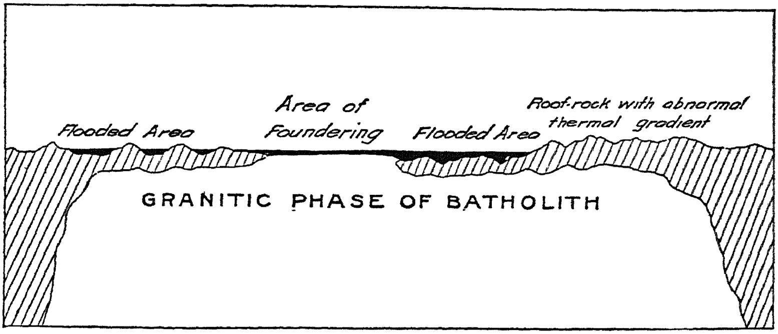

FIG. 60.—Ideal section illustrating the hypothesis that the rhyolite and the thermal phenomena of the Yellowstone Park are directly related to the foundering of part of the roof of a late-Tertiary batholith.

was certainly pre-Pleistocene and dates back at least one million years. Yet the thermal gradient within the central area is still remarkably steep, at least where geysers are active. For example, borings recently put down in the Old Faithful and Norris basins showed, respectively, a temperature of 170°C. at the depth of 124 meters and a temperature of 205° at the depth of only 81 meters.[2] While this high degree of heat may be explicable by the rise of juvenile gases and perhaps also by reactions among them, it seems reasonable to suppose that not many hundreds of meters below the surface of each geyser basin there is a great volume of hot rock. This cannot be a pile of ordinary lava flows, for these would not be able to supply the required thermal energy so long and at such rates. Does not the Yellowstone rhyolite pass down, without a break, into a batholith of Pliocene date of eruption?[3]

[1] At the author's request Dr. John Irving examined the cliffy slopes of the Madison Canyon and has reported failure to find in the rhyolite a single break that would indicate more than one outflow of the rhyolitic magma at this section. The exposure is there about 400 meters high.

[2] A. L. Day, Science, vol. 72, 1930, p. 363; C. N. Fenner and A. L. Day, Jour. Washington Acad. Sciences, vol. 21, 1931, p. 488.

[3] See R. A. Daly, Proc. Amer. Acad. Arts and Sciences, vol. 47, 1911, p. 63.

According to Cloos, the large stock of granodiorite in the Erongo district, Southwest Africa, had a roof composed of a series of lava flows that emanated from the same magma chamber. Prominent among the flows are porphyrites which are transitional into the

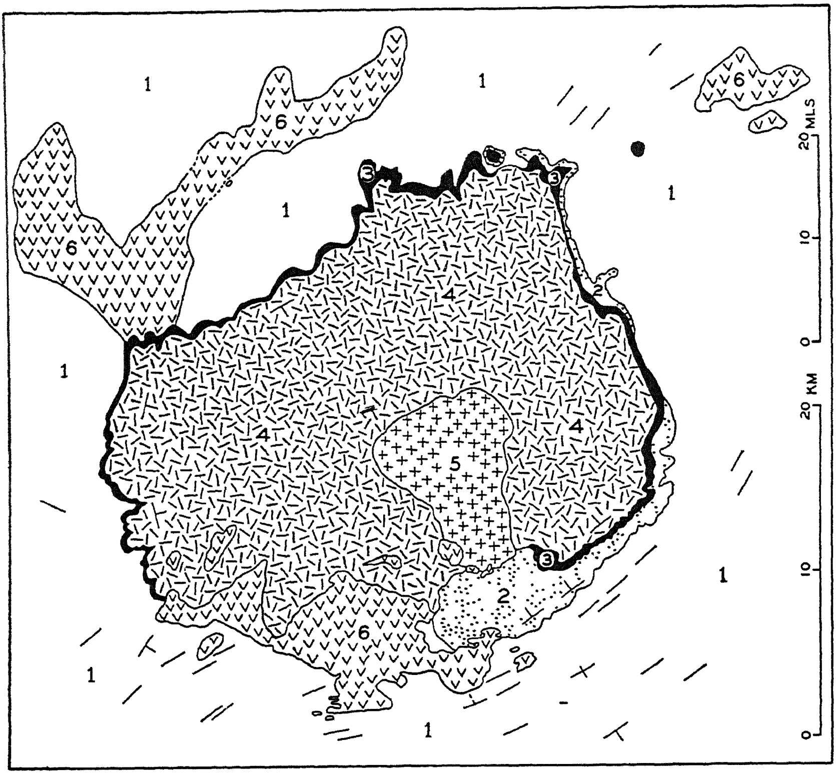

FIG. 61.—Map of the Erongo Mountain formations, Southwest Africa. *1*, Pre-Cambrian gneiss, etc.; *2*, Waterberg system of sandstones, etc., unconformable on *1*; *3*, effusive diabase, melaphyre, etc.; *4*, effusive quartz porphyry and porphyrite, sheet resting on *3*; *5*, granodiorite stock cutting *1–4*; *6*, Erongo granite, stocks cutting *1–5*. Strike and dip indicated. (*After H. Cloos, Beitr. z. geol. Erforsch. d. deut. Schutzgebiete, Heft* 17, 1919.)

granodiorite, the whole resembling a great mushroom (Fig. 61). Cloos refers this complex to the class of areal eruptions. The lavas and the underlying Waterberg sediments dip toward the center of the complex, a feature recalling the basin structure of the Bushveld Complex (see below).[1]

[1] H. Cloos, Der Erongo, Beitr. z. geol. Erforsch. d. deut. Schutzgebiete, Heft 17, 1919, pp. 176–186; Das Batholithenproblem, Berlin, 1923, p. 48; Neues Jahrb. f. Mineralogie, etc., B.B. 66 (B), Heft 1, 1930, p. 28.

An example on a smaller scale seems to be represented in the Blue Hills eruptive complex of Massachusetts. Billings found the Conway granite of New Hampshire to be covered with the chemically similar, extrusive porphyry of Pequawket and Moat Mountains.[1] In the American West and other parts of the world, batholithic granodiorites are locally capped with effusive dacite, its own chilled phase; were some of these extrusive channels really cupolas widely open to the sky?

The granite of a Pre-Cambrian "batholith" at Fox River, Wisconsin, passes into a massive rhyolite porphyry (keratophyre) and on into a rhyolite showing evidence of flow and rapid cooling at the earth's surface. The porphyry borders the granite on the south and east; the rhyolite appears in an outer belt beyond the porphyry and farther removed from the granite.[2] Is this an instance of local roof foundering? The same question arises in connection with several Swedish porphyries that seem to pass gradually into granites of large volume. The porphyries are massive, have the fine grain of extrusive rhyolites, and are directly associated with pyroclastic beds of the same chemical composition.[3]

Small-scale analogies to the imagined Yellowstone Park case are not wanting. Thus, according to von Wolff, the gabbro of Neurode, Silesia, like the locally roofless laccoliths of the Euganean Hills, illustrate "areal" eruption. Another instance of a locally roofless laccolith is reported by Robinson in Arizona (Fig. 62); still others may be represented by the Elands River and Assegai River bodies of the Transvaal.[4]

As already stated, the norite-granite-felsite body of the Bushveld Complex of the Transvaal appears to be a composite lava flow. When its hundred thousand cubic kilometers of magma welled out, the thick Pretoria sediments, which had just been deposited, were overflowed and were strongly basined under the thickening mass of liquid (Fig. 90). The basining was essentially a simple downwarp and not of the graben or taphrolithic type. The eruptive channel was probably beneath the central, thickest part of the igneous cake and is still buried out of sight.

[1] M. P. Billings, Proc. Amer. Acad. Arts and Sciences, vol. 63, 1928, p. 90.

[2] W. H. Hobbs and C. K. Leith, Bull. Univ. Wisconsin, No. 158, 1907, p. 266.

[3] A. G. Högbom, Bull. Geol. Inst. Upsala, vol. 10, 1910, sep. pp. 36, 46, 56. In vol. 5 of the same bulletins (1901, p. 19) O. Nordenskjöld notes that the extensive *hälleflintas* are transitional into, and may represent, the surface phases of adjoining granites. According to P. Eskola (Min. u. Petr. Mitt., vol. 42, 1932, p. 480) some leptites of Fennoscandia similarly pass into abyssal granitic rocks.

[4] F. von Wolff, Der Vulkanismus, Stuttgart, vol. 1, 1914, p. 439. H. H. Robinson, Prof. Paper 76, U.S. Geol. Survey, 1913, p. 83. R. A. Daly, Bull. Geol. Soc. America, vol. 39, 1928, p. 757. A. L. du Toit, Geology of South Africa, Edinburgh, 1926, p. 32.

There, possibly, crust foundering took place and so occasioned areal eruption. But for this suggestion we have as yet no direct field evidence. The Duluth gabbro and associated flows of basalt and rhyolite present the same kind of problem.

The roof-foundering hypothesis should not be condemned merely because the described cases of areal eruption are few. Conceivably

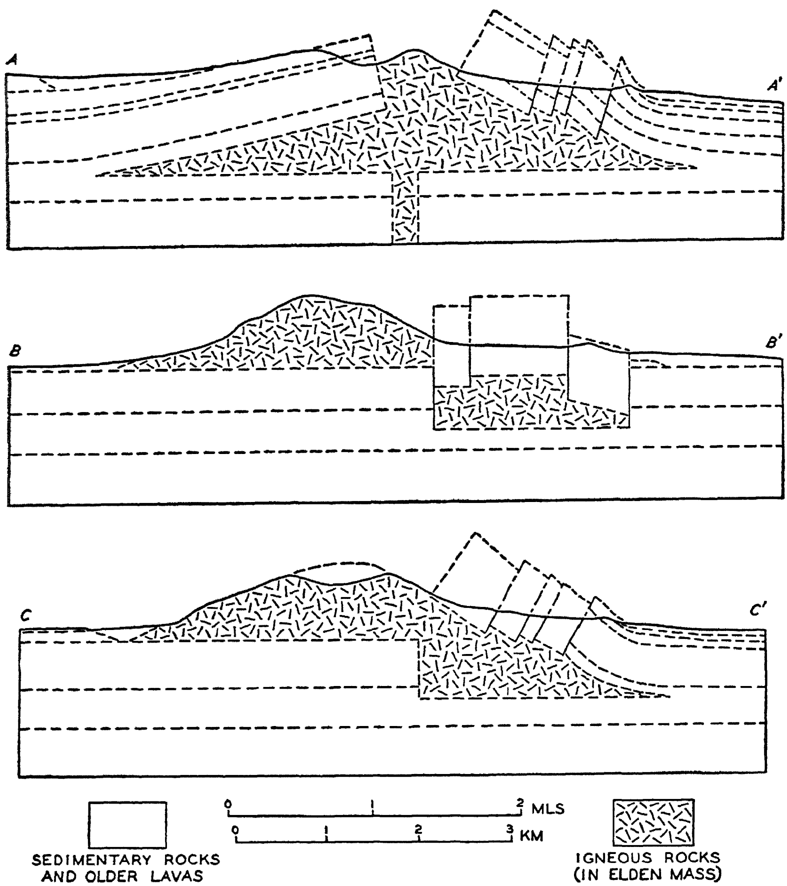

FIG. 62.—Three sections across the Elden Mountain laccolith, the magma of which broke through to the earth's surface. (*After H. H. Robinson, Prof. Paper* 76, *U. S. Geol. Survey*, 1913, *p.* 83.)

the list would already have been longer if observers had entertained the idea when at work in the field. Moreover, the rocky record of local foundering in batholiths is liable to complete destruction by erosion. The thin, scoriaceous, glassy, or lithoidal cap, formed by atmospheric chilling at the cicatrix, is one of the first victims of such erosional attack. Soon the only igneous rock left is the "plutonic" mass, which

could develop its coarse grain under that thin chill phase. In such a case the observer would be wrong if he assumed the cooling and coarse crystallization to have taken place under a continuous roof of foreign rock. Since all visible batholiths of coarse grain are old by absolute measure, erosion has had ample time to prepare deceitful appearances of the kind.

Though the roof-foundering hypothesis has, then, something to be said for it, the erection of a class of areal eruptions means a departure from the general plan of classifying igneous bodies on the basis of fairly uniform agreement among geologists as to types. The departure has been made in the interest of completeness and also to advertise the need of further field research.

III. Central Eruptions

The familiar school-book type of volcano is a local accumulation of material extruded around a single point, pericentrally. With these cones or domes may be grouped craters formed by gas fluxing, to form the class of "volcanoes of the central type."

The corresponding bodies of rock may be listed as follows:

Rock Bodies

1. Necks.
   a. Tuff necks.
   b. Lava necks, plugs.
   c. Tuff-lava necks.
2. Endogenous domes (crater domes, plug domes), spines (aiguilles), cumulo-volcanoes, mamelons.
3. Flows; superfluent, interfluent, effluent streams. Special phases and features: block lava, ropy lava, pillow (ellipsoidal) lava, tunnels, lava cascades, lava scarps, tumuli, hornitos, sand flows.
4. Cones.
   a. Tuff cones, cinder cones, ash cones.
   b. Lava cones.
      (1) Lava domes, shield volcanoes (exogenous growths).
      (2) Lava rings.
      (3) Driblet cones.
   c. Tuff-lava (normal) cones, breached cones.
   d. Cone clusters, cone chains.

The negative topographic forms associated with central eruption afford some data bearing on its essential mechanism. The more important forms are as follows:

Depression Forms (Negative Reliefs)

1. Craters.
   a. Lava pits.
   b. Maars (volcanic embryos).
   c. Blowholes.

d. Adventive craters (parasitic, lateral).
e. Nested craters.
2. Calderas (evisceration by explosion).
a. Simple calderas
(1) With lava discharge.
(2) Without lava discharge.
b. Nested calderas.
c. Sunken calderas.
3. Volcanic sinks.
a. Simple sinks.
b. Nested sinks.
4. Volcanic rents.

Rock Bodies

1. Volcanic Necks.—By denudation, volcanic channels have become exposed to some depth. The typical vent of a central volcano is found to be roughly cylindrical or neck shaped. According to the

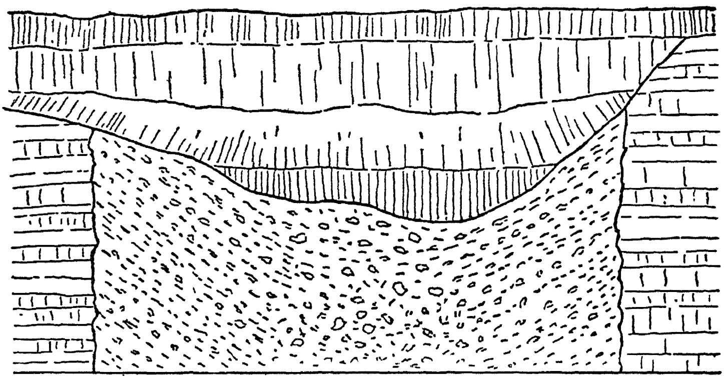

Fig. 63.—Section of volcanic tuff neck piercing and overlain by plateau basalts, Faroe Islands. Scale, 1 1300. (*After A. Geikie, Ancient Volcanoes of Great Britain, vol.* 2, London, 1897, *p.* 295.)

nature of the material filling the vents, these may be classified as *tuff necks* (Fig. 63), *lava necks* and *tuff-lava necks*.

In certain young, though extinct, volcanoes, the lava rose high in the craters, so as to form lava lakes with areas much greater than the average cross sections of the respective necks. The name "neck" is here all the more appropriate, as it joins the "head," the broad prism of lava in the crater to the "body," the subterranean magma chamber (Fig. 64). If erosion nowhere cuts through the prism, its dimensions may be mistakenly thought to be identical with those of the neck. How great the contrast may be was illustrated at Kilauea in 1909, when the main feeding pipe had a cross section apparently no greater than 100 square meters or less than 1 per cent of the area of the liquid

lake.[1] Similarly, the flaring, superficial part of a tuff-filled vent does not give a correct idea of the size of the neck beneath. Probably some of the mapped tuff necks of Scotland and other regions are seen in outcrop only at sections passing through the upper, flaring part of the vent.

In any case, central vents are always small, even minute, when compared with the sections of the larger intrusive bodies. Table 23 shows the range of diameters of mapped necks.

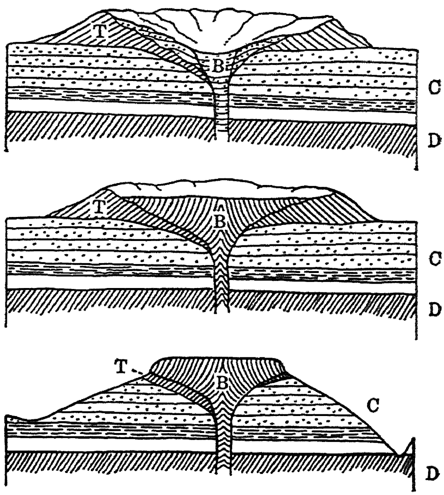

FIG. 64.—Sections showing erosion of crater charged with congealed lava. *D*, Devonian formation; *C*, trachyte tuff; *T*, basaltic tuff; *B*, massive basalt. The upper section illustrates a maar-like crater; the middle section, a lava lake; the lower section, a lava mesa left after prolonged erosion (Kuppe). (*After H. Laspeyres, Das Siebengebirge am Rhein*, 1901, *pp.* 118–119.)

2. Endogenous and Other Monolithic Domes, Spines.—Scores of otherwise normal craters have become occupied by central protrusions of highly viscous lava, freezing with a final, steep-sided domical shape. Commonly the visible surface of the new monolithic structure is separated from the rim of the crater on all sides by a moatlike depression. In some cases the viscous lava filled much or all of the moat and overflowed the rim for short distances (Fig. 67). The new lava may contain numerous blocks of rock incorporated from the walls of the vent or may have hoisted a carapace of older, solid pyroclastic material from the floor of the original crater. Probably, too, a few protrusions of similar shape represent hot, and therefore plastic, solid

[1] T. A. Jaggar (Bull. Seism. Soc. America, vol. 10, 1920, p. 158) has published an important discussion of the meaning of the expression "lava column" and has suggested several new names with which to describe his conception of the complex conditions under which a Hawaiian lava column operates.

TABLE 23.—TYPICAL SIZES OF VOLCANIC NECKS

Region	Number of necks	Range of diameters, meters
Cape Province, South Africa:		
Namaqualand	16	40–680
Wodehouse district	15	
Barkly East district	20	
Elliot district	17	4–1600
Herschel district	22	
Matatiele district	19	
Maclear	15	36–1600
Eastern Fife, Scotland	80	9–1600
Ayrshire, Scotland	60	18–1200
Swabia	132	
New Mexico	"several hundreds"	Up to 420
Leucite Hills, Wyoming	6	36–150

plugs that had filled the vent of some depth. Originating within the crater, all of these young bodies may be described as *endogenous domes*

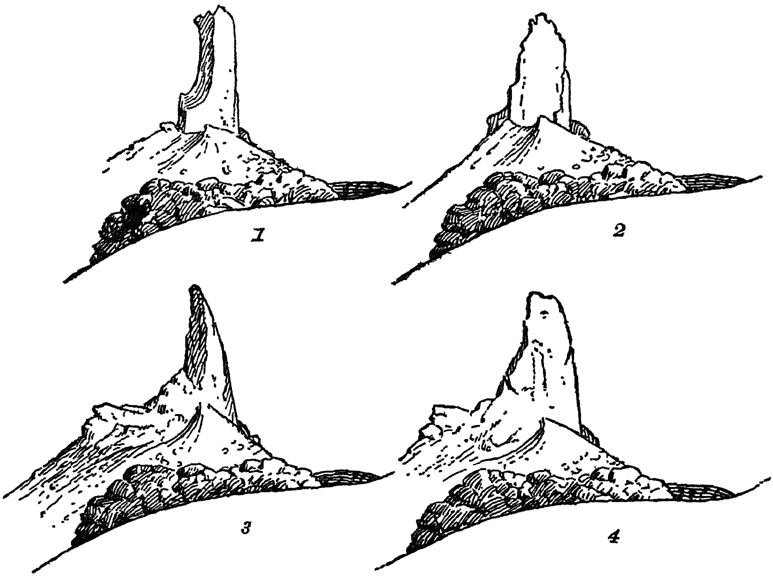

FIG. 65.—Sketches of the Mt. Pelée spine, showing its changes. *1*, Nov. 22, 1902; *2*, Nov. 25, 1902; *3*, Apr. 3, 1903, *4*, June 13, 1903. The respective heights of the summit were 1566, 1548, 1593, and 1582 meters. The elevation of the crater rim (right) is 1264 meters. (*After A. Lacroix, La Montagne Pelée et ses eruptions*, Paris, 1904, *pp.* 124, 126, 127.)

and are thus distinguished from the vastly bigger exogenous domes of the Mauna Loa or Icelandic type. Whether flowing from the main

vent or from lateral fissures, the material of an exogenous dome was accumulated well outside the crater.

The smaller bodies are endogenous in another sense, because they have grown by addition of material that rose along the internal vertical axis of each growing mass. The name is thus appropriate also for certain trachyte domes of Central France, which seem to have risen

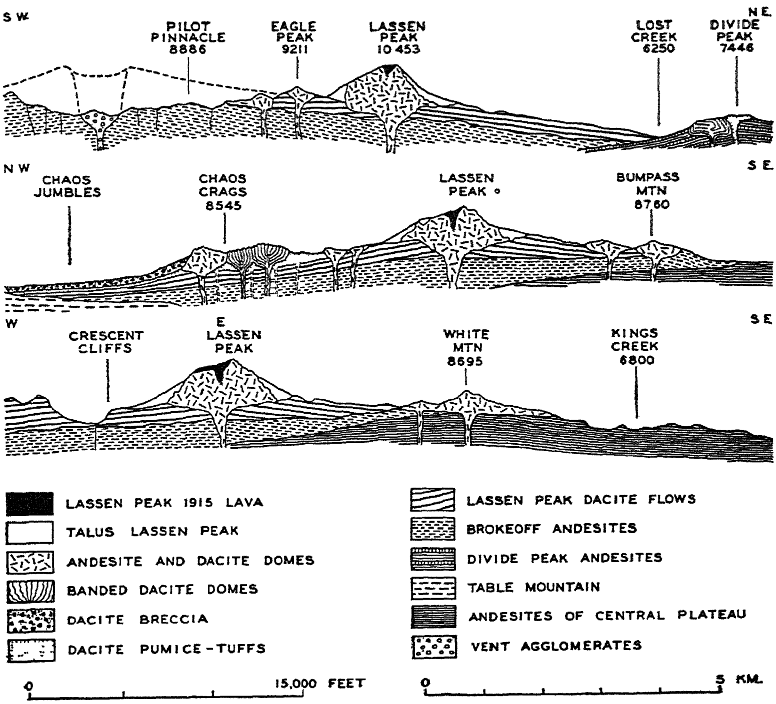

FIG. 66.—Sections of various endogenous (crater) domes, Lassen Peak district, California. (*After H. Williams, Amer. Jour. Science, vol.* 22, 1931, *p.* 386.)

through pipes in nonvolcanic rock and do not terminate in well-defined craters.

The 1902 dome of Mont Pelée, Martinique, with its famous *spine* (aiguille) was for a time one of the wonders of the world. Its tragic work at Saint Pierre led to detailed study by Heilprin, Hovey, Jaggar, and Lacroix (Fig. 65). By prolonged decrepitation the spine collapsed and the surrounding moat was filled with talus. After an explosive reopening of the vent in 1929, a second spectacular dome arose through the wreckage and is now being studied by F. A. Perret.

Other recent extrusions of the kind, though without such development of the spine form, are those at Bogosloff Island; Novarupta vent

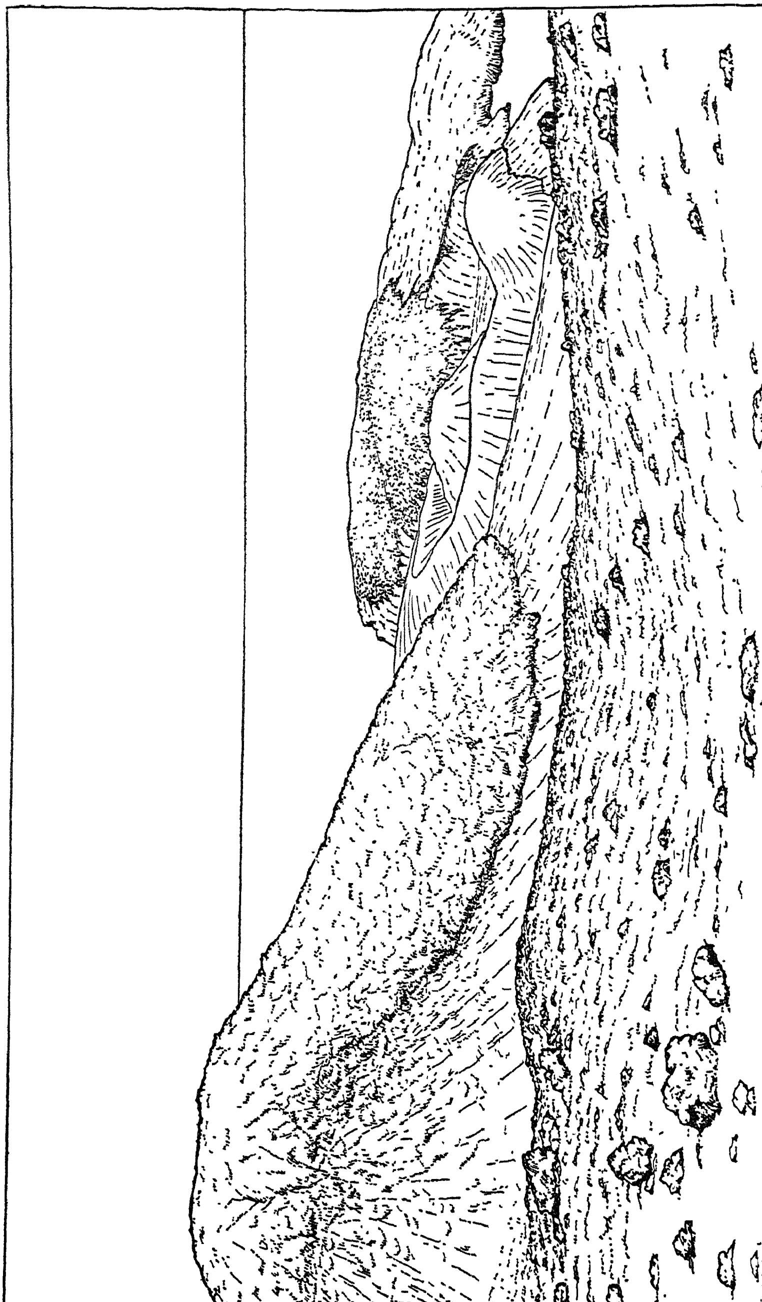

FIG. 67.—Endogenous domes, Ascension Island. On the left the White Hill trachytic dome with overflow; in the mid-ground the Wig Hill trachytic dome mantled with a basaltic "wig"; in the background the Southeast Head dome of trachyte flooded with a thin flow of trachyandesite. (*Proc. Amer. Acad. Arts and Sciences, vol.* 60, *No.* 1, *Plate* 8.)

near Mount Katmai, Alaska; Tarumai and Usu-San, Japan; Gunung Galung-gung, Java; Santa Maria, Guatemala; and Santorin.[1]

Older examples are mapped in the classic ground of the Auvergne and include the trachytic Puy Sarcoui and Puy de Dôme, with a large number dotting the Mont Dore and Cantal complexes of trachyte, trachyandesite, andesite, phonolite, and rhyolite.[2] Many trachytic domes have been discovered in Madagascar.[3] California richly illustrates the type. In the Lassen Peak region, covering 130 square kilometers, are thirteen domes, chiefly dacitic (Fig. 66). Others vary the geology of the Mono Lake region, the Marysville Buttes, and Mount Shasta.[4]

Endogenous domes are plentifully represented among the deep-sea islands, such as Tutuila, Samoa; Ascension Island (Figs. 67, 159, 163); Saint Helena Island (Fig. 162); and, according to Bebiano, the Cape Verde Islands.[5] Particularly clean-cut and well exposed are the domes of Ascension Island, one of which, the Riding School dome, showing the unusual feature of being strongly dimpled in the center, as if the magma column had contracted vertically or retreated downward to some extent.

The broad Montagnone-Maschiatta dome, one of fourteen monoliths (*Quellkuppen*) in the Island of Ischia, may be another example, the basining at the summit having taken place, in this instance, by visible step faults. Several of the Ischian monoliths (*Quellrücken*) are elongated in ground plan and appear to have issued along lines of fault rather than in craters or at single points.[6]

3. Lava Flows and Sand Flows.—Dana described the massive flows at central vents as *superfluent*, *effluent*, or *interfluent*, according

[1] Some changes of the Tarumai dome since its eruption during 1909 are described by H. Simotomai (Tanakadate), Amer. Jour. Science, vol. 44, 1917, p. 87.

[2] P. Glangeaud, Compte Rendu, Acad. Sci. Paris, vol. 168, 1919, pp. 618, 733, 1157; vol. 173, 1921, p. 780.

[3] A. Lacroix, Minéralogie de Madagascar, Paris, vol. 3, 1923, pp. 22 *ff*.

[4] H. Williams, Amer. Jour. Science, vol. 18, 1929, p. 313; Jour. Geol., vol. 40, 1932, p. 417. This author has published an admirable summary of our knowledge of volcanic domes, in Bull. Dep. Geol. Univ. California, vol. 21, 1932, pp. 51–146; see also his papers in the same Bulletin, vol. 17, 1928, p. 241, and vol. 18, 1929, p. 163. The summary brings up to date the account of the domes in the Pacific region by S. Powers (Amer. Jour. Science, vol. 42, 1916, p. 261). H. A. Brouwer (Zeit. f. Vulkanologie, vol. 6, 1921, p. 37) should be consulted for views of the new domes in Galung-gung (1919) and Ruang (1904) volcanoes. Williams's summary (p. 137) gives a useful statement of the varied lithology of domes all over the world.

[5] J. B. Bebiano, Boll. 25, Agencia Geral das Colonias, Lisbon, 1927. Recently E. Aubert de la Rüe (Revue de géog. phys. et de géol-dynamique, Paris, 1932, pp. 76*ff*.) has mapped a number of typical examples in Kerguelen Island.

[6] A. Rittmann, Zeit. f. Vulkanologie, Erg. Heft 6, 1930, pp. 30, 73.

to the place of discharge—at the summit of the volcano, at a lateral fissure, or at cavities or weak beds within the cone—in this last case without extrusion at the surface.[1]

Certain features of individual flows need explanation by any complete theory of igneous action and have received special names. Among these are *block lava*, the *aphrolith* of Jaggar, that forms the *aa*

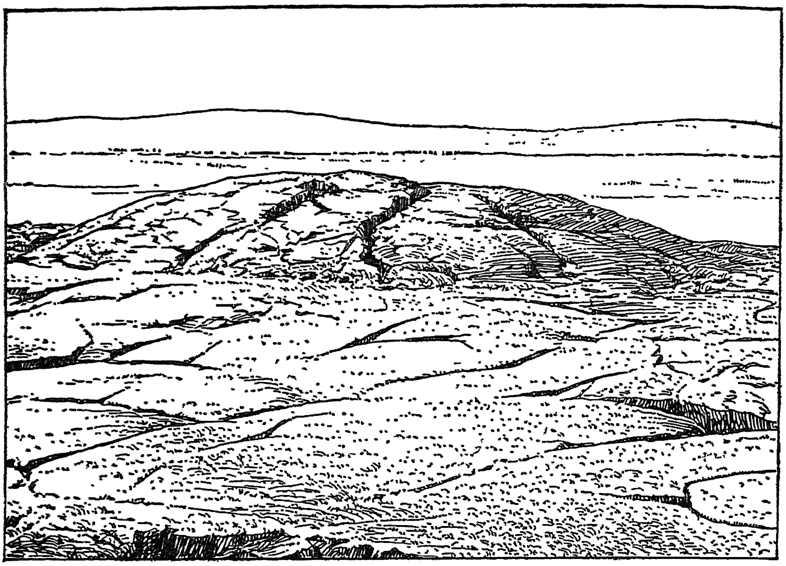

FIG. 68.—A tumulus in the floor of the Kilauean sink, Hawaii. (*From a photograph by I. Friedlaender, published in G. Mercalli's I Vulcani Attivi della Terra, Milan,* 1907, *p.* 51.)

fields of Hawaii, *les cheires* of France, and the malpais of Mexico; *ropy lava* (*pahoehoe, Fladenlava, Plattenlava,* the *dermolith* of Jaggar); *pillow lava; lava cascades; lava tunnels.* These terms are too familiar to warrant special discussion on the present occasion.[2]

Kennedy has described a number of heterogeneous ("composite") lava flows in Renfrewshire, Scotland, each having emanated from

[1] J. D. Dana, Characteristics of Volcanoes, New York, 1891, p. 2.

[2] See T. A. Jaggar, Jour. Washington Acad. Sciences, vol. 7, 1917, p. 277.

A suggestion as to the cause of the difference of habit between aa lava and pahoehoe lava was offered in 1911 (Proc. Amer. Acad. Arts and Sciences, vol. 47, 1911, p. 107). Other hypotheses have been published by H. S. Washington (Amer. Jour. Science, vol. 6, 1923, p. 419) and O. H. Emerson (*ibid.*, vol. 7, 1917, p. 277). Their relative merits will not here be discussed.

Special note should be made of the recent discovery of no fewer than thirty lava tunnels in the Mud Lake region of Idaho. One of them has the remarkable length of about 20 kilometers. See H. T. Stearns (Amer. Jour. Science, vol. 11, 1926, p. 359).

parts of a chamber where magma had already been differentiated into mobile fractions. The resulting mineralogical and chemical contrasts of phases of the flow are not due to differentiation after extrusion, which in each case was a continuous action.[1]

Many basaltic flows of the pahoehoe type exhibit swellings or low domical hills, from 10 to 20 or more meters in length and a few meters in height. These may be called *tumuli* (*Schollendome*, the *lava blisters* of Tyrrell).[2] Hundreds appear on the lava fields of Hawaii (Fig. 68).

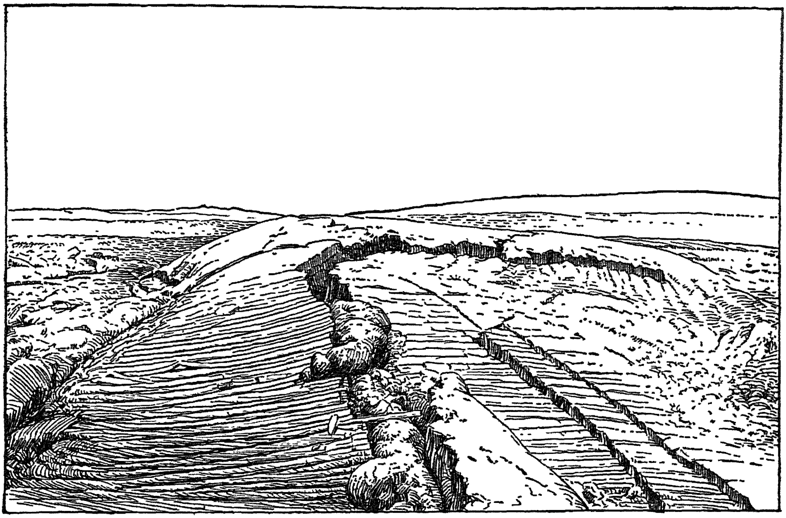

Fig. 69.—A tumulus in the floor of Kilauea. During the updoming, liquid lava issued from the cracks characteristic of this volcanic form. (*From a photograph by the author*, 1909.)

They have been raised by the local hydrostatic pressure of still-fluid lava beneath the already chilled crust of a somewhat inclined flow. The ropy crust is characteristically fractured by the pressure, and sometimes the liquid has escaped through the cracks (Fig. 69). The intumescence is analogous to the deformation of the roof of a laccolith, and to the "squeeze-ups" of the Sunset Crater flow, Arizona.[3]

As the term is used, *hornitos* seem to include vents situated on the backs of flows and delivering either blobs of viscous lava (*driblet cones*) or small volumes of ash or tuff.[4]

[1] W. Q. Kennedy, Geol. Mag., vol. 68, 1931, p. 166.

[2] "Tumulus" is here used in its original, Latin sense—a swelling-up. Splendid illustrations of them and other *Kleinformen* of volcanic origin are given in I. Friedlaender (Zeit. f. Vulkanologie, vol. 1, 1914, p. 222; see also succeeding numbers of this important journal).

[3] H. S. Colton and C. F. Park, Science, vol. 72, 1930, p. 579.

[4] For examples see E. H. Pacheco, Mem. R. Soc. Española Historial. Natura, vol. 6, 1910, p. 251.

Sand flows, represented at Mount Katmai (Valley of the Ten Thousand Smokes) and Mont Pelée, are products of the terrible *nuées ardentes* and dependent upon explosion, but gravity also controls, so that such a deposit may be listed as a special kind of directly volcanic flows. According to Glangeaud, Tertiary pyroclastic beds of this kind are extensively spread among the volcanic complexes of Mont Dore and the Cantal, Central France.[1]

4. Volcanic cones are pyroclastic, lava formed, or of mixed constitution.

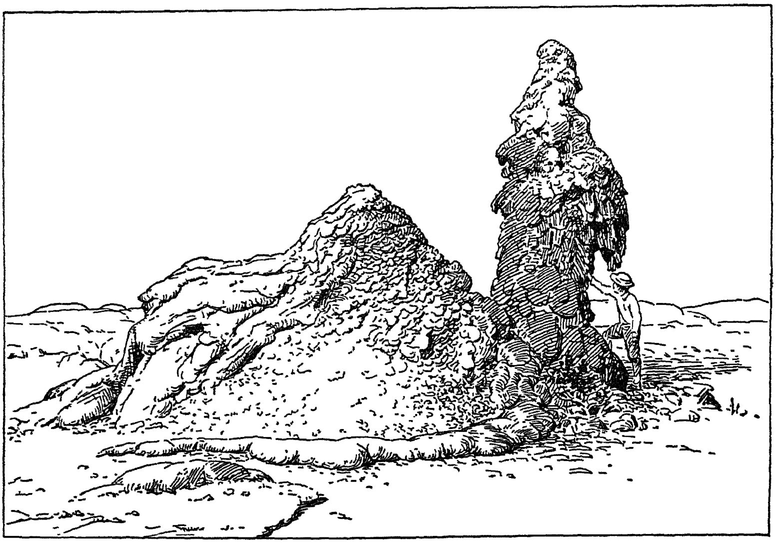

FIG. 70.—Driblet cone near the Kamaklaia cones, Hawaii. (*From a photograph by H. E. Wilson, July* 14, 1911.)

Pure types of *tuff cones, ash cones,* and *cinder cones* are of small size. In *lava cones* massive flows greatly predominate. Absolutely pure types, devoid of pyroclastic interbeds, are rare. Among them are the driblet cones, whether built on the backs of ordinary flows or not (Fig. 70).

Lava rings are extraordinarily large driblet cones, formed by the symmetrical upbuilding of the walls of a lava lake by the congealing of intermittent overflows from the lake. In 1893, such a self-built rim was seen around the Halemaumau lake at Kilauea.[2] There is a good example on Hualalai, Hawaii, southeast of the summit.

[1] P. Glangeaud, Compte Rendu, Acad. Sci. Paris, vol. 167, 1918, p. 1076; vol. 173, 1921, p. 780.

[2] For admirable illustrations see W. T. Brigham, The Volcanoes of Kilauea and Mauna Loa of the Island of Hawaii, Honolulu, 1909, Plate 50

Exogenous lava domes ("shield" volcanoes) are more voluminous products of successive flows, often, as already noted, alternating with deposits of pyroclastic nature. The type is Mauna Loa (Fig. 134).

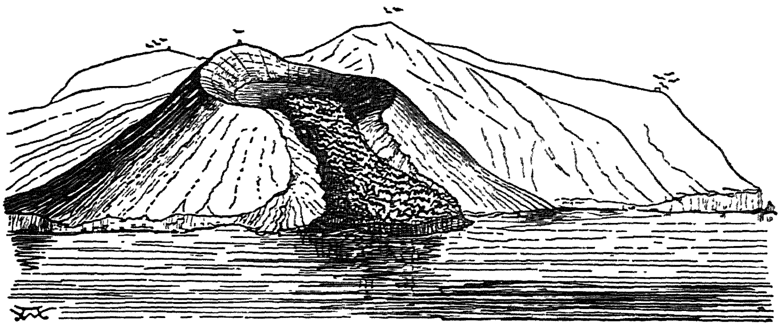

FIG. 71.—Pumice cone breached by the outflow of an obsidian lava current, Island of Lipari. (*After J. W. Judd, Volcanoes, New York,* 1881, *p.* 124.)

Sixteen examples were described by Thoroddsen and others in Iceland. The thickness of the individual flow is moderate. More than one

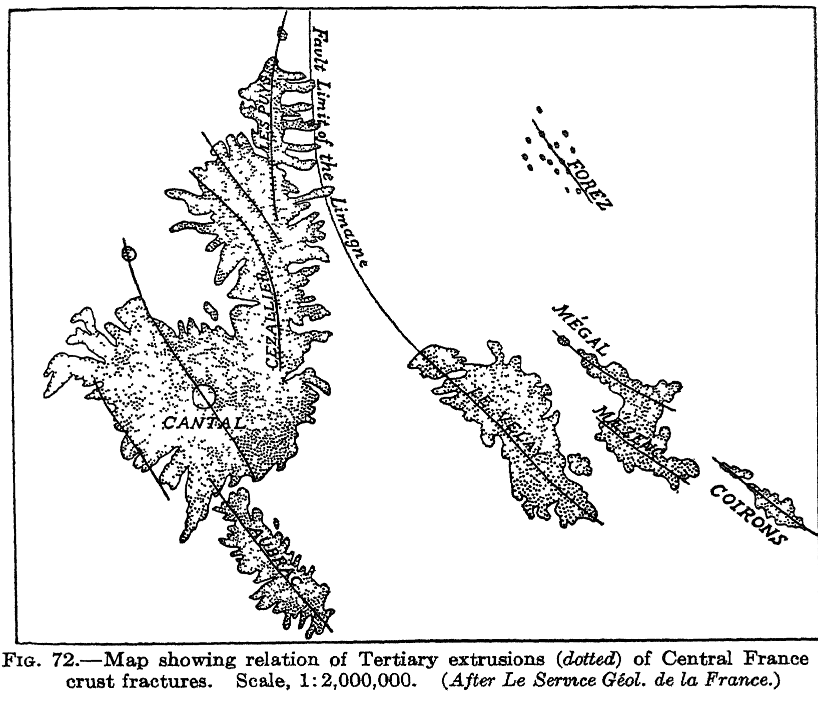

FIG. 72.—Map showing relation of Tertiary extrusions (*dotted*) of Central France to crust fractures. Scale, 1:2,000,000. (*After Le Service Géol. de la France.*)

hundred were counted in the 600-meter cliff of Molokai Island. An average thickness of no more than about 6 meters characterizes the flows of the dramatic cliffs of Haleakala, Island of Maui, and a similar

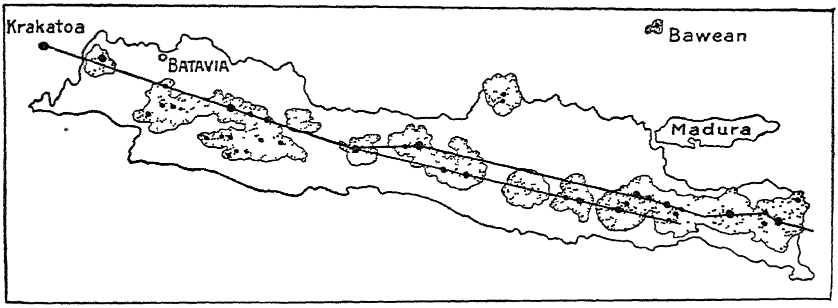

FIG. 73.—The cone chains of Java (*dotted*). Heavy black dots represent principal vents. Scale, 1:10,000,000. (*After R. D. M. Verbeek and R. Fennema, Description géologique de Java et Madoura, Amsterdam*, 1896.)

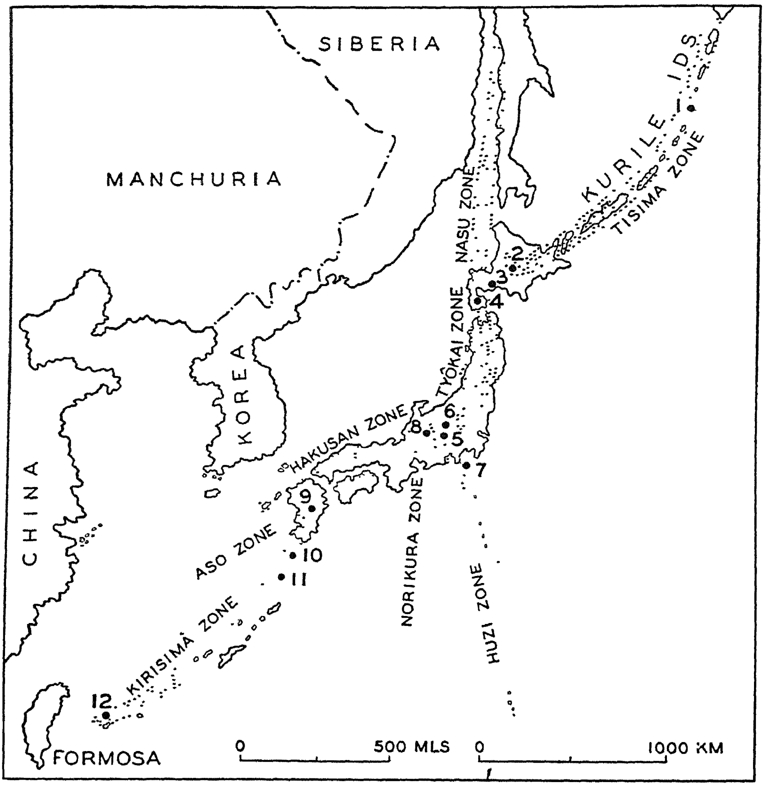

FIG. 74.—Neovolcanic cone chains of Japan and (numbered) localities of volcanic activity during the period 1924–1931. 1, Matuwa Zima, 2, Tokati Dake; 3, Tarumai San; 4, Komaga Take; 5, Asama Yama; 6, Kusatusirane; 7, Osima Mihara Yama; 8, Yake Dake; 9, Aso San; 10, Kutinoerabu Zima; 11, Suwanose Zima; 12, Hatoma Zima. (*After H. Tanakadate, Japanese Jour. Astr. and Geophysics, vol.* 9, *No.* 1, 1931, *p.* 61.)

estimate is probably not far wrong in the case of the many flows exposed in the canyon walls of Kauai. For the Kau district, Island of Hawaii, Stearns gives an average of a little more than 3 meters.[1] Probably the general average is somewhat less than the world average for the plateau basalts.

Tuff-lava cones (stratovolcanoes, "normal" cones, cones of "mixed type") are abundant and include most of the celebrated living volcanoes.

Breached cones, so named by Judd, are exemplified in Fig. 71.[2]

Finally, we note the familiar *clusters* and *chains* of cones, the former without discernible linear arrangement (Figs. 72 to 74). Each of these areal grouping of units clearly represents an important genetic problem.

Depression Forms

The negative reliefs of volcanic origin still lack systematic, universally accepted nomenclature and definition. The classification to be presented is the result of combining certain elements in existing definitions.

1. Craters.—A crater is a pit forming the normal surface expression of a central vent. The great majority have flaring walls. The flare is usually continuous but may be interrupted by subordinate vertical cliffs. Under normal conditions of activity the flat floor of the crater (liquid, pasty, or solid lava) is not many times more extensive than the cross section of the neck beneath.

The flare is due to one or more of three causes: explosion, slumping, or melting of the wall rocks. As a rule, the gases producing explosion are chiefly contained in the neck (vent) itself, and the form typically resulting is an inverted cone. Under the circumstances the area of the crater's floor can differ little from that of the cross section of the pipe beneath. Subsequent slumping of the more or less shattered walls increases the flare, while diminishing, for the time at least, the area of liquid lava. Renewed explosion clears out such debris and restores the typical relation of floor area to the size of the vent. We have seen that lava lakes are characteristically wider than their feeding pipes—a fact due in part to the melting and sapping of the crater walls by the hot gas-charged liquid. Yet even the Hawaiian craters have floors which, on the average, are not far from matching the criterion suggested for craters in general.

When first formed, a crater may be fissure-like, but, by the mechanism that keeps it open (explosion, slumping, and melting), the ground plan soon becomes subcircular.

[1] H. T. Stearns, Water-supply Paper 616, U.S. Geol. Survey, 1930, p. 60.

[2] J. W. Judd, Volcanoes, New York, 1881, p. 123.

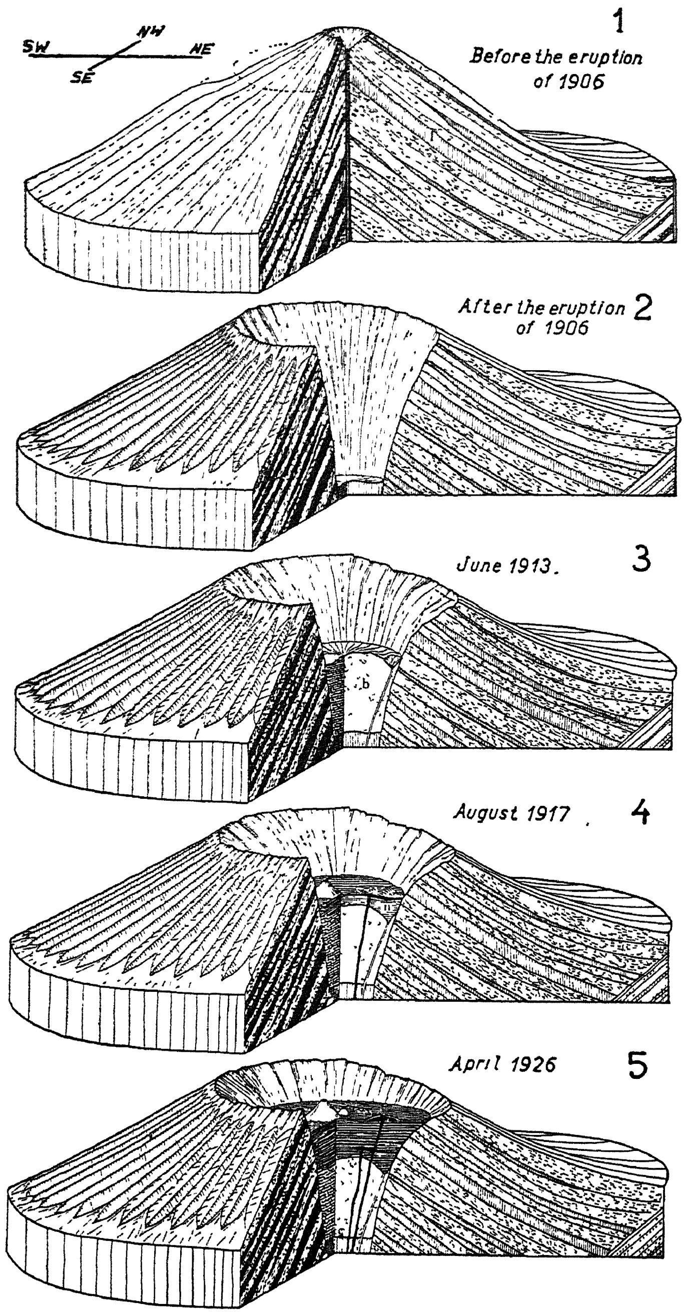

FIG 75.—Stages in the recent history of the crater of Vesuvius. (*From B. G. Escher, Leidsche Geol. Mededeelingen, vol.* 5, 1927, *p.* 51, *Plate* 16.)

Perret has shown how, in 1906, the volcanic stream of gas enlarged the vent and crater of Vesuvius down to the depth of perhaps 1000 meters. He has graphically illustrated the gradual filling of the crater during the later years[1] (see also Fig. 75).

Lava pits are craters visibly floored with massive lava, liquid or solid. The Hawaiian pits (Fig. 76) are specially instructive, for they have evidently perforated the older lava plateau, not by explosion but by melting (gas fluxing).

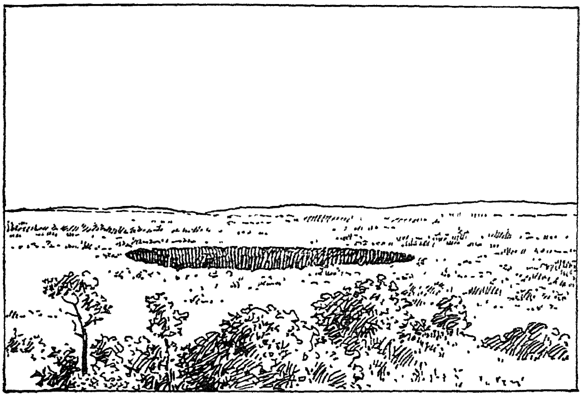

FIG. 76.—Distant view of a small pit crater in the Puna district, Hawaii. The well-like crater is about 60 meters in diameter. (*From a photograph by the author,* 1909.)

Maars are relatively flat-floored craters of explosion at vents that are either coneless or else provided with inconspicuous cones. Examples are abundant in Swabia (Fig. 135), and Reck has recently published unusually fine illustrations of maars in Abyssinia.[2]

Blowholes are the minute craters formed on the surfaces of thick flows; they are visible on many driblet cones.

Adventive (parasitic, lateral) *craters* are those opened on the flanks of large cones (Fig. 77).

Nested Craters.—Sometimes central vents show crater in crater. The smaller, interior crater has evidently been produced after there had been some diminution of the rate of heat transfer from depth,

[1] F. A. Perret, The Vesuvius Eruption of 1906, Pub. 339, Carnegie Inst. of Washington, 1924, p. 100.

Abundant illustration of craters of explosion in the United States is due to N. H. Darton (The Scientific Monthly, November, 1916, p. 417).

[2] W. Branco, Schwaben's 125 Vulkan-Embryonen, Tübingen, 1894. For the Eifel maars see R. Lepsius, Geologie von Deutschland, ler Teil, Stuttgart, 1887–1892, p. 333. H. Reck, Zeit. f. Vulkanologie, vol. 12, 1930, p. 290

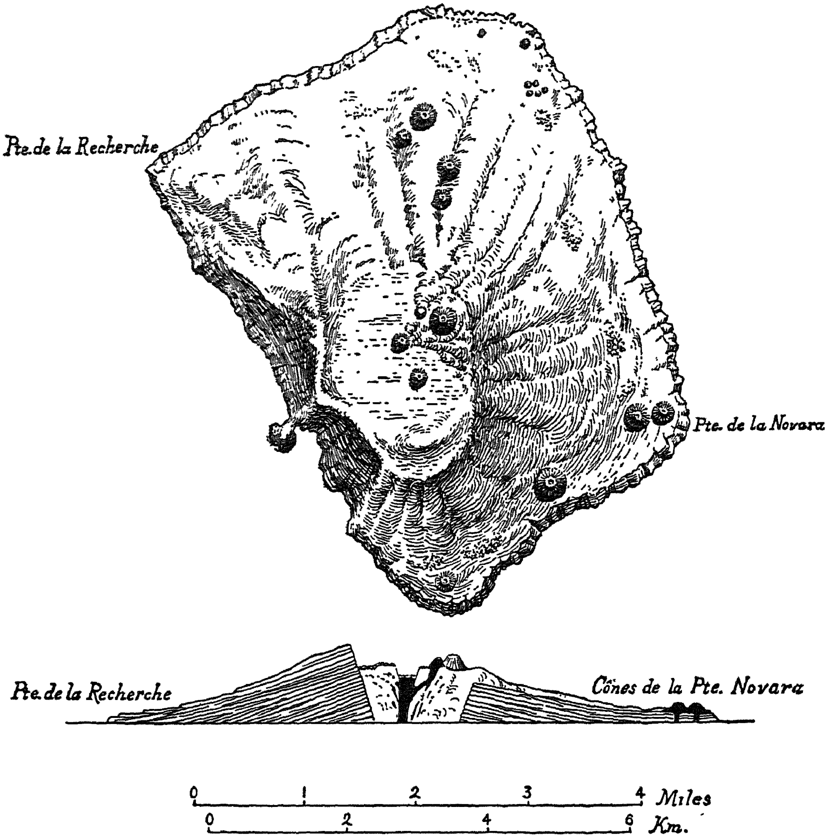

FIG. 77.—Map and section of Amsterdam Island volcano, showing adventive cones and craters. (*After C. Vélain, Mission de l'île Saint Paul, Paris*, 1880, *Plate* 26.)

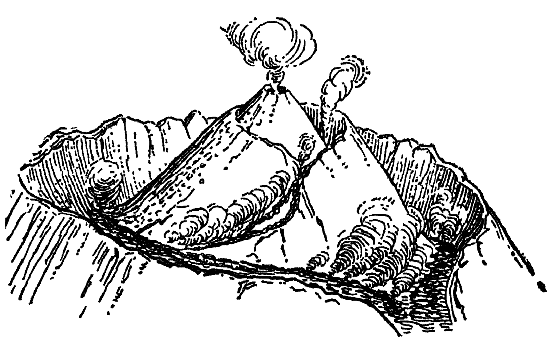

FIG. 78.—The nested craters of Vesuvius, from a sketch by Sir. W. Hamilton. (*Campi Phlegraei*, 1799.)

whereby also the cross section of the feeding pipe was also diminished[1] (see Figs. 78 and 79).

2. Calderas.—Here usage and definition are in confusion. By general agreement, "caldera," as a technical physiographic term, will refer only to a large basin, walled in completely (circus) or partly (amphitheater). A number of writers, particularly some in Germany,

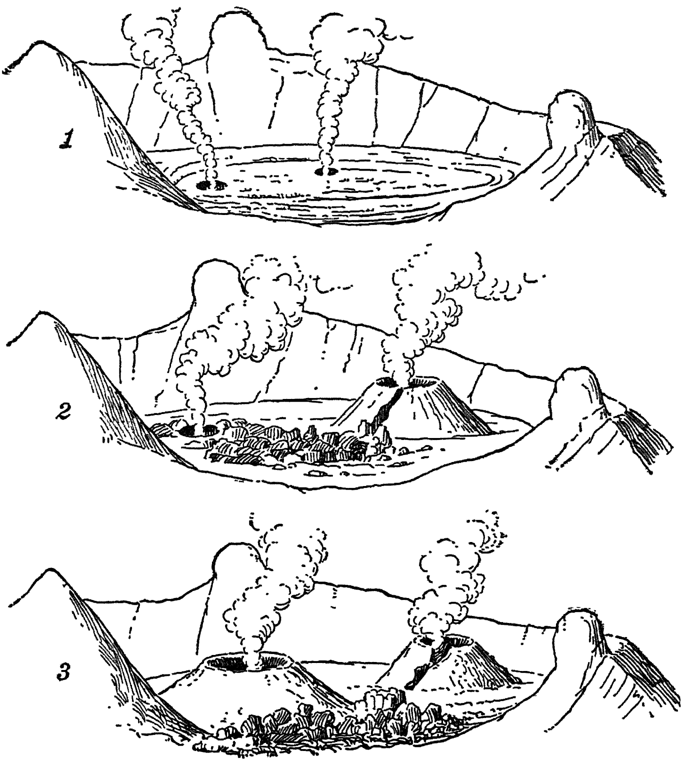

FIG. 79.—Nested craters of Etna in the early part of the nineteenth century. Three stages of the summit crater: *1*, years 1804–1805; *2*, years 1805–1809; *3*, years 1810–1816. (*After W. S. von Waltershausen, Der Aetna, vol.* 2, 1880, *p.* 304.)

use the word in this broad, purely topographic sense. As a matter of fact, such basins are not readily classified on a genetic basis, so that the geologist needs some such broad category for his reports of field study. Basin after basin is being mapped, but their students remain more or less baffled as to origins. Hence the *Calderaproblem*, as named in Germany, is always with us. Simplified somewhat by the exclusion of

[1] *Cf.* R. D. M. Verbeek and R. Fennema, Description géologique de Java et Madoura, Amsterdam, Atlas Bijlage 18, Fig. 71; H. Abich, Erläuternde Abbildungen geologischer Erscheinungen beobachtet am Vesuv und Ætna, Berlin, 1837, Plates I and II.

all purely erosional basins from the class of calderas, the problem still remains open. Was a given basin formed by explosion, by subsidence, or by a combination of the two? Until that question is answered all along the line, a broad name for the larger volcanic basins is needed.

Accordingly, other nations might conceivably follow certain German authorities (Friedlaender, Gagel, Kanter, Reck, Schaffer, Spethmann, von Wolff) and recognize (1) explosion calderas or calderas of explosion (*Explosionscalderen*); (2) subsidence calderas or calderas of subsidence (*Einbruchscalderen*); and (3) explosion calderas deepened by subsidence. Already this has been done more or less systematically by Cleland and by Pirsson of the United States.

Outside Germany few geologists have comprehensively discussed this genetic problem and the expediency of sharpening definitions and therefore ideas expressed in professional publications. The United States Geological Survey, following Dutton, defines caldera as a basin of subsidence and excludes basins of explosive origin. Sapper and Bergeat have adopted the same convention. On the other hand, most British writers (Lyell, A. Geikie, Oldham, Harker), some French writers (de Martonne, Haug), the Italian Mercalli, the Japanese Tanakadate, and the Americans Lahee, Hodge ("Mt. Multnomah"), and Washington (Val del Bove, Etna) regard calderas as explosion forms. Kayser also shares this view in the case of most large volcanic basins.

Evidently the situation needs to be clarified. The writer has offered one way out of the difficulty—by restricting caldera to mean a large volcanic basin due to explosion, other large basins due to volcanically controlled subsidence being called "volcanic sinks." Thus bats would not be grouped with birds.

A few writers have adopted the idea, and it is significant that Jaggar, the supreme authority on the volcanoes of Hawaii, where Dutton evolved his definition, does not follow him or the ruling of the United States Geological Survey but describes the Hawaiian pits as sinks, not as calderas.[1] Further, while von Fritsch and Reiss had, in 1868, favored explosion as the cause of the seven calderas of the Azores, both Hartung and Lyell, still earlier, were at least sympathetic with the same principle as applicable in the Canary Islands.

Thus narrowed in meaning and distinguished from volcanic sink, there is also need of recognizing a difference between a caldera and an ordinary crater of explosion. The area of the floor of a caldera is so large as to be of another order when compared with the cross section of the associated vent. Such cross section is generally no larger than that of a common volcanic neck. Both form and volume of a caldera

[1] T. A. Jaggar, Bull. Seism. Soc. America, vol. 10, 1920, pp. 189, 196.

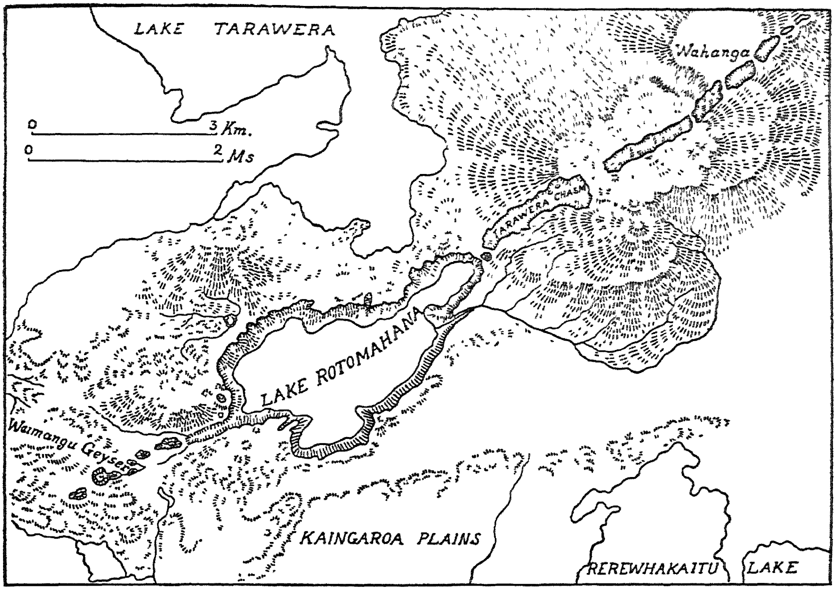

FIG. 80.—The Tarawera rift and Rotomahana caldera, New Zealand. (*After A. P. W Thomas, whose map is reproduced by J. M. Bell, Geog. Jour.*, 1906.)

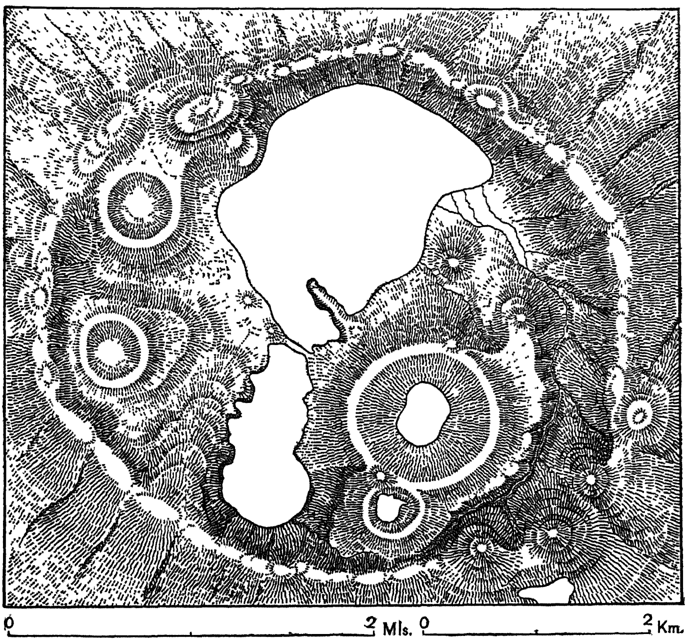

FIG. 81.—Map of the Caldeira of the Sete Cidades, San Miguel Island, Azores. Several younger craters appear in the caldera. (*After G. Hartung, Die Azoren*, 1860, *atlas*.)

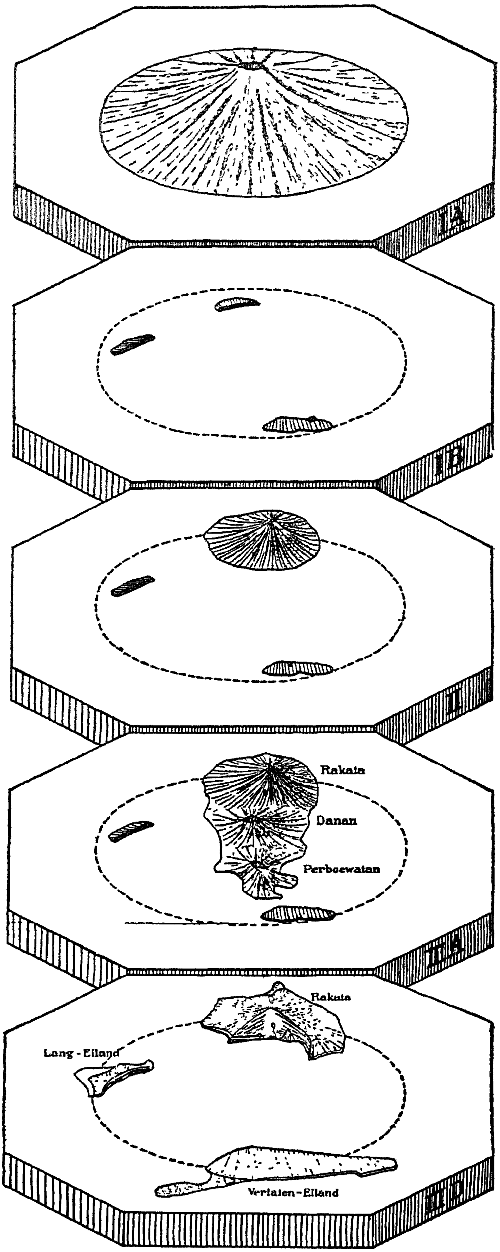

FIG. 82.—Stages in the history of Krakatoa. *I, A.* Hypothetical great central cone of andesite. *I, B.* Disappearance of the cone (through subsidence?). *II.* Building of basaltic cone of Rakata. *III, A.* Addition of andesitic cones of Danan and Perboewatan, which with Rakata form the island Krakatoa. *III, D.* Island remnants after the explosions of August, 1883; second formation of a great central basin. (*After B. G. Escher, Excursie-gids voor Krakatau, Weltevreden,* 1919.)

forbid belief that the explosion was due merely to the tension of juvenile gas within the column of liquid magma. The summit caldera of the Japanese Bandai-San is an extreme case, where the prodigious explosion of 1888 eviscerated the cone without the exposure of any liquid magma whatever.[1]

The meaning of this contrast of conditions will be noted in Chapter XV. Though transitional forms are to be expected, and the assignment of a small explosion basin to the class of crater or caldera may be difficult, such a trouble cannot outweigh the advantage of clearly distinguishing the two kinds of topography. Any uncertainty is here no more disturbing than that felt when classification of most other natural objects is attempted.[2]

Illustrations of *simple calderas* are given in Figs. 80 to 82. According to Ross, the largest example yet mapped is that in the Valles Mountain region of New Mexico.[3]

Von Wolff lists twenty-one calderas, including depressions due to subsidence as well as explosion. Among the larger basins are:

	Diameters, Kilometers
Aso-San, Japan	14 by 23
Circus, Teneriffe	20 by 12
Idjen (I)	20 by 16
Idjen (II)	20 by 16
Alban Hills, Italy	11.2 by 10.2
Santorin	11.1 by 17 4
Aniakchak, Alaska	10.8 by 9.2
Valles Mountains	25 by 29

The conditions leading to a caldera may recur on a smaller scale at the same center, so that a second basin of the class is developed inside the first. The process may be repeated several times. The resulting more or less concentric basins may be described as *nested calderas* (Fig. 83).

In Java and elsewhere subsidence is said to have followed caldera explosion. The basins of such composite origin may be called *sunken calderas* (Fig. 84). According to Wagner, the remarkable "salt pan" of the Transvaal is an example. There, after a "tremendous phreatic explosion" or series of explosions, the caldera sank down along a ring-shaped fault. Wagner regarded the basin of Lonar Lake, India, originally described by Oldham, as of similar history.[4]

[1] S. Sekiya and J. Kikuchi, Jour. Coll. Sci. Univ. Tokyo, 1889, p. 106.

[2] Similarly with the distinction between the smaller volcanic sinks and pit craters (due to withdrawal of magma, whether juvenile or the product of gas fluxing).

[3] C. S. Ross, Trans. Amer. Geophys. Union (Nat. Research Council), 1931, p. 185.

[4] P. A. Wagner, Mem. 20, Geol. Survey South Africa, 1922, p. 27.

3. Volcanic Sinks.—Each volcanic basin of engulfment or downfaulting has, typically, a floor area many times greater than the cross section of the associated vent.

Simple volcanic sinks are illustrated by Fig. 85.[1]

Du Toit believes the Modder Fontein volcano of South Africa to represent a sink, so eroded as to have lost its character as a topographic depression. Its tuffs and agglomerates dip inward, because of subsidence of the original volcanic cone.[2]

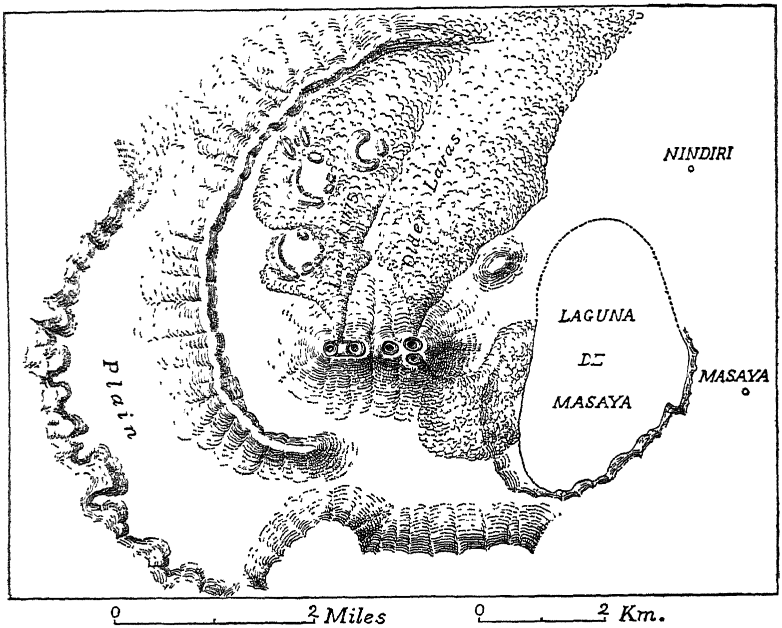

FIG. 83.—Nested calderas at the Masaya volcanoes, Nicaragua. The outer escarpment is the eroded lip of the older caldera. Within it is seen part of the younger caldera ring, within which are nested the active Nindiri-Masaya cones. (*After K. von Seebach, Abhand. k. Ges. Wiss. Gottingen, Phys. Kl., vol.* 38, 1892, *p.* 58 *and Taf.* 9.)

Nested Sinks.—More or less concentric sinks have been mapped in Hawaii and elsewhere (Fig. 86). Even Halemaumau, which for many years had been a type of ordinary pit crater, became, in 1924, a sink nested within the fault walls of the greater Kilauea sink. Jaggar estimates the volume of matter ejected at Halemaumau during the paroxysm of that year as 800,000 cubic meters, while the volume "engulfed" was about 200 million cubic meters, or 250 times as much.[3]

[1] Possibly the Tengger depression is better described as a sunken caldera.

[2] A. L. du Toit, 16th Ann. Rep. Geol. Comm. Cape of Good Hope, 1912, p. 132.

[3] T. A. Jaggar, Mon. Bull. Hawaiian Volcano Observatory, vol. 12, 1924, p. 122. Compare E. G. Wingate's map of Halemaumau (September, 1932), published in The Volcano Letter, December, 1932, with Fig. 121 of this book.

Mount Gambier, South Australia, furnishes another example, called by Fenner a case of a "collapsed crater."[1] Verbeek has specially emphasized the occurrence of both simple and nested sinks in Java.[2]

FIG. 84.—The sunken caldera of Santorin. Scale, 1:150,000. (*After F. Fouqué, Santorin et ses eruptions*, 1879; *his map here copied from a copy in Neumayr's Erdgeschichte, published by the Bibliographisches Institut.*)

The proposed definitions thus lead to the following genetic classification:

MAJOR VOLCANIC BASINS

I. Calderas.
  a. Simple calderas.
  b. Nested calderas.
II. Volcanic sinks.
  a. Simple volcanic sinks.
  b. Nested volcanic sinks.
III. Sunken calderas.

[1] C. Fenner, Trans. Roy. Soc. South Australia, vol. 45, 1921, p. 195.

[2] R. D. M. Verbeek and R. Fennema, Description géologique de Java et Madoura, Amsterdam, 1896.

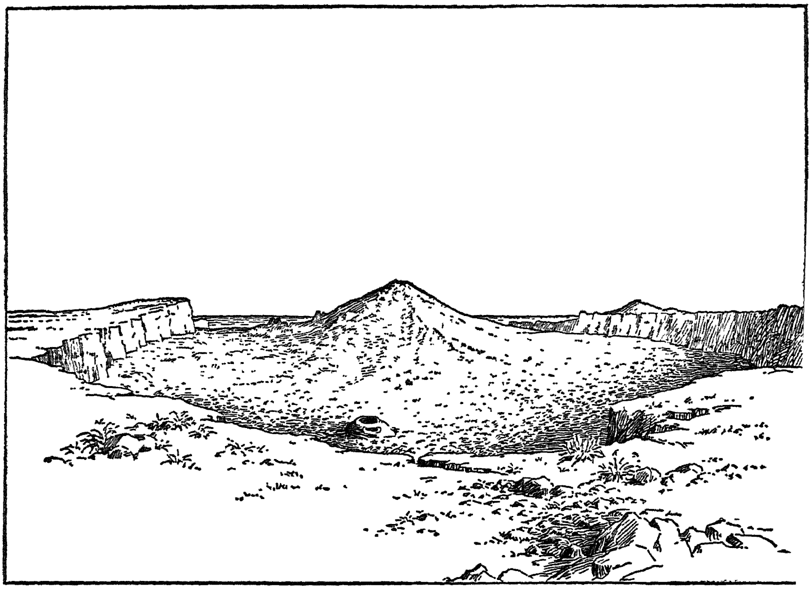

FIG. 85.—View of the Enclos of Réunion, a volcanic sink, in which is the extinct con piton Bory. (*After C. Vélain, Mission de l'île Saint Paul*, 1880, *Plate* 10.)

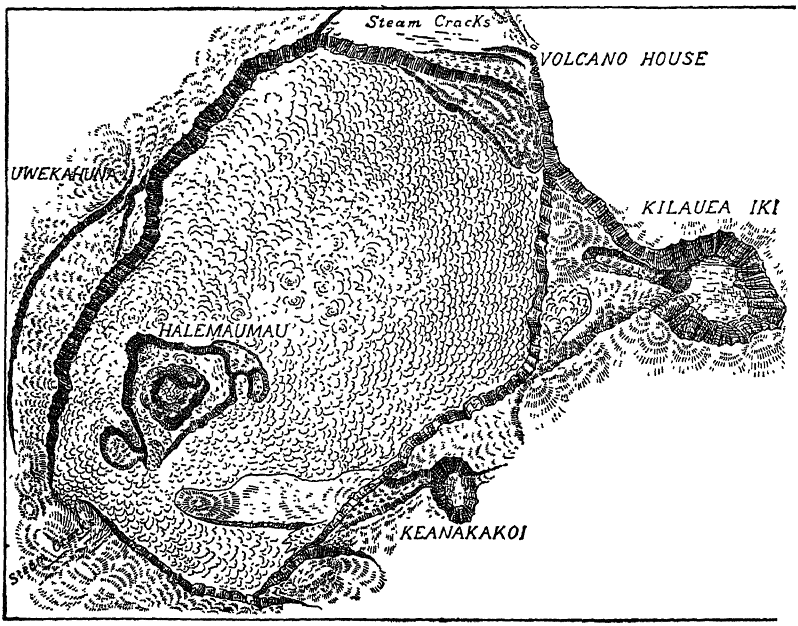

FIG. 86.—Map of the Kilauea sink, Hawaii, in 1886 Scale, 1:57,600. (*Af* *Government map, by F. S. Dodge.*)

Some economy of words and greater convenience of use are manifest when that scheme is compared with the alternative classification, founded on "caldera" as a blanket name for all large volcanic basins:

CALDERAS (= MAJOR VOLCANIC BASINS)

I. Explosion calderas or calderas of explosion.
  a. Simple explosion-calderas.
  b. Nested explosion-calderas.
II. Subsidence calderas or calderas of subsidence or volcanic sinks.
  a. Simple subsidence-calderas or volcanic sinks.
  b. Nested subsidence-calderas or volcanic sinks.
III. Calderas of composite origin (explosion followed by subsidence).

4. Volcanic Rents.—The great gaping depression at the summit of Haleakala in Maui, Hawaiian Islands, is commonly described as a "crater," but Dutton long ago pointed out the fallacy in so doing. He prefers to call this form also a caldera, remarking that it is "strictly homologous" with the main depression (sink) at Kilauea.[1]

During a visit to the summit in 1909, the author failed to find evidence of this homology. General circumferential faulting, which is topographically so clear at Kilauea, is not evident on the walls of the vast depression on Haleakala. On this problem Dana writes:

> In my "Exploring Expedition Report" I suggest that the mountain was fissured across along the lines of the two discharge-ways, and the eastern block shoved off a mile or two. But a subsidence of the masses that occupied them into caverns below, leaving the walls as fault planes, may be more probable. The abyss which received them in this case had been prepared during a long period of undermining through ejections. Still there is some reason to believe in the grander view of a subsidence of the whole eastern block, across the cross-fracturing.[2]

Brigham accepted Dana's first hypothesis and called the depression a "rent." There are certain difficulties with this interpretation. These have led Powers and also Hinds to prefer Dutton's idea of an origin in ordinary faulting. Both Powers and Hinds agree, however, that final judgment in the matter must await further detailed study in the field.[3] Conceivably the opening of this famous "crater" was begun with the formation of a true rent (displacement dominantly horizontal) and completed by slumping (downfaulting) of "splinters" (Hinds).

Much older rents, filled with injected magma as the "sliding" displacements took place, are possibly represented in the eastern part

[1] C. E. Dutton, 4th Ann. Rep., U.S. Geol. Survey, 1884, p. 105.

[2] J. D. Dana, Characteristics of Volcanoes, New York, 1891, pp. 277–278.

[3] S. Powers, Bull. Geol. Soc. America, vol. 28, 1917, p. 512. N. E. A. Hinds, Bull. Geog. Soc. Philadelphia, vol. 23, 1925, p. 25.

of Saint Helena island and at the center of the southwestern caldera of the Island of Mull. In each case more or less advanced erosion has obscured much of the evidence; nevertheless, at Saint Helena particularly, the field proof of prolonged tension of the rent kind seems clear (see the note on multiple dikes, page 91).[1]

[1] R. A. Daly, Proc. Amer. Acad. Arts and Sciences, vol. 62, 1927, p. 57; Proc. Amer. Phil. Soc., vol. 64, 1925, p. 296 (footnote)

PLATE II.—Incandescent (orange-yellow) basaltic Alika flow from Mauna Loa, running about 16 kilometers per hour. (*Photograph by T. A. Jaggar, Bull. Hawaiian Volcano Observatory, vol. 7, 1919, pp. 136, 156.*)

(*Facing p* 172)

PART II: A GENERAL THEORY

CHAPTER IX

OUTER SHELLS OF THE EARTH

INTRODUCTION

The foundation of petrology was laid during the nineteenth century, when a great store of indispensable detailed observations was supplied from the field and, after Sorby led the way, in the laboratory. The pioneers were naturally analytical and chiefly concerned with the differences among rocks. However, Von Buch, Bunsen, Von Waltershausen, Cotta, Von Richthofen, Zirkel, Rosenbusch, Durocher, Fouqué, Kjerulf, Brögger, Darwin, Scrope, Lyell, Jukes, Geikie, Judd, Goodchild, Teall, Dana, Dutton, King, Gilbert, and Lawson kept guiding useful observation by offering suggestions regarding the conditions below the surface of the planet. The masters of the new craft were feeling their way to fundamentals, but a systematic theory of the earth's constitution was hardly possible until the geophysics of the present century began to provide data for more fruitful and sounder deduction. Recent geophysical discoveries are wholesomely limiting the range of speculation and so helping us better to understand the outer shells of the globe and to locate the original home of eruptive material.[1]

As far back as 1855, the principle of isostasy was recognized by Airy, who offered a theoretical explanation. Four years later Pratt suggested the attenuation theory of isostasy, essentially different from that of Airy. In 1889, Dutton invented the word "isostasy," the name of the principle which, within the next twenty-five years, was to be proved by Putnam, Gilbert, Hayford, Bowie, Lambert, and Helmert. These geodesists demonstrated a close degree of crustal balance, obtaining wherever wide areas of the earth's surface were investigated. Others, including Niethammer, Hecker, Duffield, Meinesz, Heiskanen, and Prey, have helped to corroborate the world-wide, though not absolutely perfect, rule of isostasy. The actual departures of the

[1] The text of the new, instructive "Petrography and Petrology" (New York, 1932) shows that its author F. F. Grout also sees the need of steady questioning of the earth's interior.

earth's skin or "crust" from hydrostatic equilibrium with respect to the underlying material are seldom large, and blocks with diameters exceeding 400 kilometers appear to be in nearly perfect balance with their neighbors. Thus the oceans are deep because the rocks beneath, down to a depth of some tens of kilometers, have average density higher than the average density of the horizontally opposed continents.

The "light" rocks of the continents are chiefly felsic. They belong to the interrupted earth shell called "the Sal" by Suess. Wegener, following Pfeffer, objected to this mnemonic word on the ground of possible confusion with the Latin for "salt" and introduced "Sial" as a preferable contraction for "silica-alumina rocks."[1] The objection is not weighty and is not likely to affect the retention of "Sal" and "salic" in systematic petrography. Rapidly winning its way, "Sial" is already in common use as a convenient name for the whole assemblage of high-floating continental rocks. These include not only a small proportion of basic injections, rocks erupted from the underlying Sima (shell of silica-magnesia rocks), but also limestones and other formations which are poor in silica and alumina. Hence "Sal," useful in petrography, really differs in meaning from "Sial," useful in general geology and geophysics. In this book "Sial" will mean the composite of varied but dominantly acid rocks (granites, granodiorites, quartz diorites, their allies and derivatives), typically represented in the plateau-like continents.

Apparently Suess believed the Sial to constitute a complete earth shell. On the other hand, the general absence of quartz-bearing rocks among the lavas, tuffs, and breccias of the deep-sea volcanoes long ago led some geologists to suspect the absence, or at least extreme thinness, of the Sial over half of the earth's surface. This suspicion became strengthened by the multiplying proofs of isostatic balance between continent and ocean. In fact, geological opinion here tends toward unanimity. Over wide areas, Sialic rocks seem to be lacking under the deep oceans, though drowned blocks of the Sial, like the massifs of the Azores, Cape Verde Islands, Kermadec group, and Kerguelen, are found at varying distances from the main shores of each ocean basin. The Mid-Atlantic Swell is probably the submerged top of an unusually wide and thick band of Sialic material. Gutenberg and a few other seismologists believe it necessary to postulate a thin, continuous layer of Sial all the way across the Atlantic basin. The evidence for this hypothesis needs support, and the values of gravity at sea, found by Meinesz, suggest failure of Sialic rocks beneath much

[1] E. Suess, Das Antlitz der Erde, Vienna, vol. 3, 1909, p. 626. A Wegener, Die Entstehung der Kontinente und Ozeane, Braunschweig, 2d ed., 1920, p. 22.

of the deep Atlantic, which thus has a crustal constitution probably approximating that under the mid-Pacific.[1]

THICKNESSES OF THE OUTER SHELLS

Some local, geosynclinal prisms of stratified rocks have maximum thicknesses of 10 to 20 kilometers, but the average thickness of the sedimentary cover, unconformably resting upon the Archean (early Pre-Cambrian) crystallines of the continents, can hardly much exceed 2 kilometers. Beneath that interrupted "pellicle" of post-Archean sediment is the more essential part of each continental division of the Sial, the "Basement Complex." By ordinary geological methods the general nature of this complex may be inferred, to the depth of a half-dozen kilometers. An estimate of its whole thickness is a problem for the geophysicist. Two different geophysical methods of attack on this question have been developed. The results from both methods give the same order of magnitude for the total thickness of the Sial in areas of normal continental relief.

One of the methods is seismological. From earthquake records, Oldham, Milne, and Wiechert deduced the existence of a strong discontinuity under the continents at a depth which was estimated to be 50 to 60 kilometers. With later, much more ample data, A. and S. Mohorovičić, corroborated by Gutenberg and others, have found a major discontinuity under Central Europe at nearly the same depth.[2] Still more recently Jeffreys has expressed doubt about the evidence for so great a depth and estimates it to be no more than 30 to 40 kilometers, under Northwestern Europe at least.[3]

Between that major discontinuity and the surface of the continent is a subordinate but decided discontinuity, independently read out of seismograms by S. Mohorovičić, Conrad, Jeffreys, Gutenberg, Matuzawa, and Tillotson. Estimates of its depth, as well as that of the main discontinuity, are given in Table 24, which also states the velocities of the longitudinal (V) and transverse (v) waves running from earthquake centers through the corresponding layers of rock (earth shells).

The dotted lines of the table signify discontinuities. Where for a given layer only one velocity is stated, this means an average for

[1] B. Gutenberg, Zeit. f. Geophysik, Jahrg. 3, 1927, p. 376; Gerlands Beitr. z. Geophysik, vol. 16, 1927, p. 239. V. Meinesz, Geog. Jour., vol. 71, 1928, p. 144.

[2] A. Mohorovičić, Jahrb. d. meteorol. Observ. in Zagreb (Agram), Jahrg. 9, Teil 4, Abschn. 1, 1909; S. Mohorovičić, Gerlands Beitr. z. Geophysik, vol. 17, 1927, p. 180; B. Gutenberg, Der Aufbau der Erde, Berlin, 1925, p. 116, with references.

[3] H. Jeffreys, Mon. Not. Roy. Astr. Soc., Geophys. Supp., vol. 1, 1926, p. 402; *ibid.*, vol. 1, 1927, p. 492; Gerlands Beitr. z. Geophysik, vol. 17, 1927, p. 417; The Earth, 2d ed., Cambridge, Eng., 1929, p. 100.

TABLE 24.—WAVE VELOCITIES AND DISCONTINUITIES IN CONTINENTAL SECTORS

Authority	Region	Layer	Depth, km	V, km/sec	v, km/sec
S. Mohorovičić	Central Europe	A	0–40	5 54–5.66	
		B	40–60	6 22–6 40	
		C	60+	7 90	
B. Gutenberg	Central Europe	A	0–30	5 5–5.7	3 2(?)–3 3
		B	30–45	6 25–6 3	3 7
		C	45–60 or 70	7.9–8.0	4 4–4 5
		D	>60 or 70	7.9	4 4
E. Tillotson[1]	Central Europe	A′	0–4	5.0	3 3
		A″	4–17	5.5	3 36
		B	17–42 3	6.3	3 65
		C	42 3+	7.8	4 35
H. Jeffreys	Western Europe	A	0–10	5.4–5 6	3 3
		B	10–35	6.3	3.7
		C	35+	7.8	4 35
T. Matuzawa	Japan	A	0–20	5.0	3 15
		B	20–50	6.2	3.7
		C	50+	7.5	4.5
B. Gutenberg	California	A′	0–14	5.54–5.59	3.23
		A″	14–25	6.05	3 39
		B	25–31	6.83	3.66
		C′	31–39	7.6	4.24
		C″	39+	7.94	4 45

[1] Using Tillotson's values of V and v in layers A′, A″, and C, A. W. Lees (Mon. Not. Roy. Astr. Soc., Geophys. Supp, vol. 3, 1932, p. 13) gives new estimates for the thicknesses of the Central Europe layers and finds some evidence of a discontinuity in layer B. The thicknesses are as follows: A′ (sedimentary), 1 kilometer; A″ ("granitic"), 11 5 kilometers; B′, 15 kilometers (V, 6.3 kilometers per second and v, 3.65 kilometers per second); B″, 10 kilometers (V, 7.0 kilometers per second and v 3.95 kilometers per second). The limits of possible thickness of B′ + B″ are 22 kilometers and 33 kilometers, and the indicated thickness of each of these sublayers is described as "very doubtful."

that layer, the seismologist concerned not being able to give the law of variation within the layer. Some increase of velocity with depth is probable, and its estimated amount is shown where a range of velocity appears in the columns.[1]

The differences among the results, though doubtless due partly to real heterogeneity of the crust, reflect the difficulty of interpreting the instrumental graphs of near earthquakes and of securing exact times of travel. Any percentage error in the measurement of the speed of the waves means practically half as great a percentage error in the deduced value of the seismically effective elasticity; we shall soon see how this principle affects the accuracy with which the earth's interior can be diagnosed. The whole problem of wave velocities and discontinuities is now engaging the efforts of the ablest seismologists, and there is good reason to anticipate fairly close agreement in the solution for the normal Sialic sector.

In the following discussion it will be assumed that the levels separating layers A, B, and C of Table 24, but corresponding to the typical Sial of a continental plateau, are respectively 30 kilometers and 40 kilometers down. It is understood that these figures are not regarded as exact and that the boundaries of the shells are not perfectly sharp. Indeed, sublayers, transitional in chemical and physical properties, would be expected. Thus the lowest part of the crystallized Sima may well carry interstitial glass, small in amount but increasing downward until the wholly vitreous shell (D) is reached.

Using the wave velocities and the results of high-pressure experiments on the cubic compressibility of rocks, several geophysicists have deduced the petrographical nature of layers A, B, and C, with the thicknesses respectively given in Table 24. Their opinions are summarized in columns 1 to 4 of Table 25.[2]

[1] S. Mohorovičić, Gerlands Beitr. z. Geophysik, vol. 14, 1916, p. 187; *ibid.*, vol. 17, 1927, p. 180. B. Gutenberg in Müller-Pouillet, Handbuch der Physik, Braunschweig, vol. 5, part 1, 11th ed., 1928, pp. 670, 762, 822; Bull. Seism. Soc. America, vol. 21, 1931, p. 219; Handbuch der Geophysik, edited by B. Gutenberg, Berlin, vol. 3, Lief. 1, 1930, p. 453; Gerlands Beitr. z. Geophysik, vol. 35, 1932, p. 6. E. Tillotson, Mon. Not. Roy. Astr. Soc. London, Geophys. Supp., vol. 2, 1931, p. 416. H. Jeffreys, The Earth, 2d ed., Cambridge, Eng., 1929, p. 100. T. Matuzawa, Nature, vol. 125, 1930, p. 615; Bull. Earthq. Research Inst. Tokyo, vol. 7, 1929, p. 257. *Cf.* V. Conrad, Akad. Wiss., math.-naturw. Kl., Mitt. der Erdbeben-Kommission, N.F., No. 59, 1925.

M. Hasegawa (Zeit. f. Geophysik, vol. 6, 1930, p. 97) has located the main discontinuity under Japan at the depth of 55 kilometers.

[2] See references above. Also L. H. Adams and E. D. Williamson, Smithsonian Rep. for 1923 (1925), p. 253; L. H. Adams and H. E. Gibson, Proc. Nat. Acad. Sciences, vol. 12, 1926, p. 282, and vol. 15, 1929, p. 723; A. Holmes, Trans. Geol. Soc. Glasgow, vol. 18, 1929, p. 566.

TABLE 25.—PETROGRAPHY OF THE EARTH'S OUTER SHELLS

	1	2	3	4	6
Layer	S. Mohorovičić	Jeffreys	Adams, Gibson, and Williamson	Holmes	Daly
A	Granite and granodiorite with syenite	Granite		Averages near granodiorite	Granite dominant
B	Diorite and gabbro	Diorite or vitreous basalt	Granite or granodiorite	Amphibolite and granulite	"Piezo-granite" merging downward into "piezo-granodiorite" (and "piezo-diorite"?)
C	Crystalline pyroxenite and peridotite (continues to great depth)	Eclogite or crystalline or vitreous dunite (continues to great depth)	Crystalline peridotite (possibly vitreous, according to Williamson and Adams, 1923)	Peridotite: crystalline or vitreous or both in vertical sequence, to depth of 2900 kilometers	"Piezo-gabbro" dominant
D	....	. . .. .	. ...	... .	Vitreous basalt, passing downward, perhaps rapidly, into more femic vitreous basalt (and then vitreous peridotite?)

The determination of wave velocities at the depths concerned is probably exact enough to furnish a point of departure, however the case may be with layer D. The use of those velocities in diagnosis of the petrographical nature of the layers is, however, affected with some uncertainties. Assuming that the rocks are perfectly elastic, and therewith assuming the applicability of the standard equations connecting wave velocity with the elasticity, the cubic compressibilities of the various rocks are calculated. These compressibilities have been directly compared with those found by high-pressure experiments on the commoner types of plutonic rock. The matching of these quantities has led to most of the diagnostic results shown in columns 1 to 4, Table 25.

The first of the uncertainties referred to is due to our ignorance as to the relation between the high-pressure compressibility and the seismically effective compressibility. The difference may be small and yet enough to cause important errors in diagnosis.[1]

[1] Among recent writers who also entertain the possibility of such contrast of the two moduli are B. Gutenberg (Handbuch der Geophysik, vol. 2, Lief. 1, Berlin 1931, pp. 521, 562) and H. Reich (*ibid.*, vol. 6, Lief. 1, 1931, p. 26).

Second, there is a question of perhaps greater importance: is it right to make comparison with rocks which, though plutonic, have all crystallized comparatively near the earth's surface? We know that load metamorphism changed Pre-Cambrian rocks, both igneous and sedimentary, at depths no greater than a few kilometers. From granite came gneiss, denser and more incompressible. In depth gabbro is metamorphosed into the denser and more incompressible amphibolite. As a rule the chemical composition of such recrystallized rock is not changed, and the compressibility falls faster than the density increases. Hence at the depth of a few tens of kilometers material that would, under present conditions, crystallize as gabbro near the surface may have the volume compressibility of a normal igneous rock more basic than gabbro. Accordingly, different writers have suggested, for depths of 40 to 60 kilometers, eclogitic or amphibolitic material, the high-pressure equivalent of basalt or gabbro. But the exact effect of static or other metamorphism on basaltic material at these depths is really unknown, and it seems better to give the expected metamorphic product a more noncommittal name. For this "piezo-gabbro" is proposed. Similarly we should consider the possible, if not probable, existence of what may be called "piezo-granite," "piezo-granodiorite," etc., at depth. Each of the pressure phases would have bulk moduli larger than those of the corresponding plutonic rocks of normal high-level habit.

Again, we do not know how far each earth shell departs from chemical homogeneity with increasing depth. However the shell was formed, we should expect it to become increasingly basic and less compressible from its top downward. If this be true, none of the columns in Table 25 is likely to give an exact picture of the outer earth shells.

Finally, there is some question as to the accuracy with which the wave velocities in each layer have been determined. As already implied, the velocities in layers A to C are known with a considerable degree of assurance. Yet any residual errors in those affect judgment concerning wave velocities in layer D. The reasons for recognizing the existence of this layer will be discussed later. Meantime it may be noted that a quite small error in the wave velocities assumed for layer D may make a relatively great difference in the petrographical diagnosis of the layer.

Since V increases relatively little all the way to the minor discontinuity (at a rate near that expected in a uniform rock under the given increasing pressure and consequent decreasing compressibility), the chemical composition of the Sialic, dominantly granitic material probably changes but little down to that level.

The rather sudden jump in V at the minor discontinuity has still to receive final explanation, but it seems barely possible that this break is located at the level where low quartz inverts to high quartz.[1]

The wave velocities in the layer between the two upper discontinuities are those expected if the quartz-bearing Sial, while somewhat more mafic than granite, extends down to the main discontinuity.

To conclude: seismology has already furnished precious data regarding the shelled condition of the continental sectors of the globe. While awaiting more accurate measurements of wave velocities in, and thicknesses of, the different shells, we may hope for definite information as to the values of the elastic moduli that are *effective in the propagation of earthquake waves.* Even when we have these, we shall still have to query the effects of load metamorphism before deciding on the petrographical nature of the different layers. Meantime seismological results do not appear to forbid our picturing the earth shells as represented by the last column of Table 25—a scheme which in principle has been worked out for reasons quite independent of seismology (see also Table 32, page 248).

Another check on the preferred value for the normal thickness of the continental Sial is suggested by recent works on isostasy. When "Igneous Rocks and Their Origin" was written, the Pratt-Hayford theory of isostasy and Hayford's estimate of the depth of compensation—113 to 122 kilometers—were accepted by many geologists and geophysicists. Later, Bowie, also basing his computations on the Pratt-Hayford theory, obtained 96 kilometers as the most probable depth of compensation within the area of the United States, though from the data won from regions outside the mountainous reliefs the most probable depth turned out to be about 60 kilometers.

Believing that this theory is unsound, the author could not, in 1914, accept any of the larger values for the depth of compensation. None of them could be easily reconciled with the facts of geology.

The Airy theory has only recently been applied in anything like an adequate way. With sea-level "thickness of the crust" taken as 50 kilometers, Heiskanen proved the gravitational data for the United States to be better explained by the Airy principle than they are by any investigated form of the rival theory. In the case of the Alps he found, for a depth of compensation of 107 kilometers according to

[1] See Chapter X, page 237, for references. The offered explanation of the discontinuity seems able to account for most of the increase of V, if this increase is as sudden and as great as indicated in Table 24. However, such sharpness of contact between layers A and B is not demonstrated, and actual seismograms do not exclude the possibility that the transition from granite to a more mafic rock like granodiorite may be completed at a level not far from the level of the quartz inversion.

the Pratt-Hayford hypothesis and for an Airy sea-level thickness of the crust of 41 kilometers, approximately the same mean anomalies of gravity.[1]

Still more recently Heiskanen has made the natural suggestion that the Airy theory should be modified by assuming horizontal variation of density in accordance with the relief of the crust. Heiskanen's chosen scheme of this variation is somewhat arbitrary, but the result is significant. With 50 kilometers taken as the sea-level thickness of the crust, he obtained a smaller mean anomaly of gravity for the United States than that given by the Pratt theory with Hayford's depth of compensation at 113.7 kilometers. Further, the former result is about as satisfactory as the results derived from the original Airy theory with assumed depth of 40 kilometers or 60 kilometers for the Sial.[2]

Different from all three schemes is the distribution of densities implied by the crust-substratum theory here proposed. This theory assumes the Sial to be more radioactive than the Sima, as well as a better conductor of heat. The net effect is to give the suboceanic crust a greater thickness than the crust of a continental sector.[3] It is further assumed that the density of Sial and of Sima vary in both horizontal and vertical directions. Exact statement of densities is out of the question, and an indefinite range of choices within the limits set by the general theory is admissible. Nevertheless the particular set of choices represented in Fig. 87 will illustrate the contrast with the classic explanations of isostasy.

The five divisions of the drawing correspond to an earth sector (A) covered by 5.2 kilometers of sea water, a sector (B) covered by 4.2 kilometers of sea water, a sector (C) with the rocky surface at sea level, a sector (D) with the rocky surface at the normal height of a continent, 800 meters above sea level, and a sector (E) with the rocky surface at 3 kilometers above sea level. The crystalline Sima is shaded; the vitreous Sima, or substratum, left blank. The depths of the discontinuities are indicated in kilometers, their calculation being based upon the supposition that in sector D the Sial is 40 kilometers thick and the crystalline Sima 20 kilometers thick, the crust under the

[1] W. Heiskanen, Veröfft. Finnisch. Geodät. Inst., Helsinki, No. 4, 1924, pp. 77, 78.

[2] W. Heiskanen, Zeit. f. Geophysik, vol. 3, 1927, p. 217; Ann. Acad. Sci. Fenn., ser. A, vol. 36, No. 3, 1932, p. 133. H. Jeffreys (The Earth, 2d ed., Cambridge, Eng., 1929, p. 198) states that "the depths found by Heiskanen are upper limits to the depths where the compensation occurs."

[3] There is a certain rough analogy with the Airy theory, the Sial corresponding to Airy's "crust" of uniform density, and the crystallized Sima to Airy's denser magma in which he supposed the crust to float.

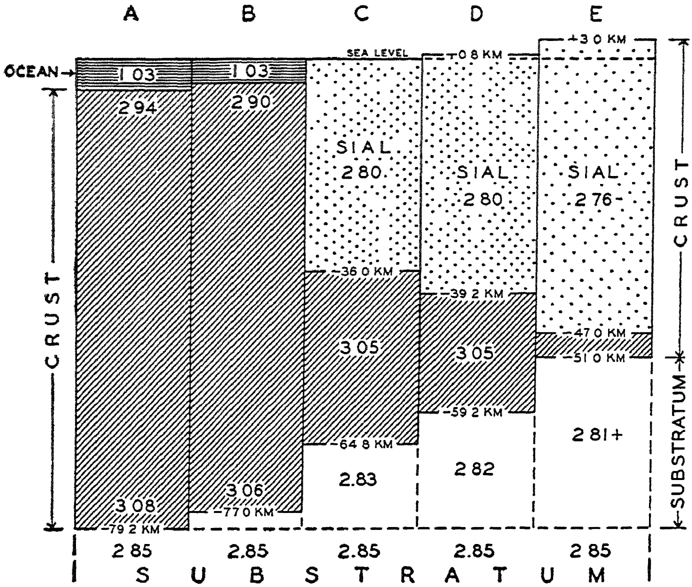

FIG. 87.—Illustrating isostatic equilibrium of the earth's crust, according to one of the many conceivable schemes of density implied by the crust-vitreous substratum hypothesis.

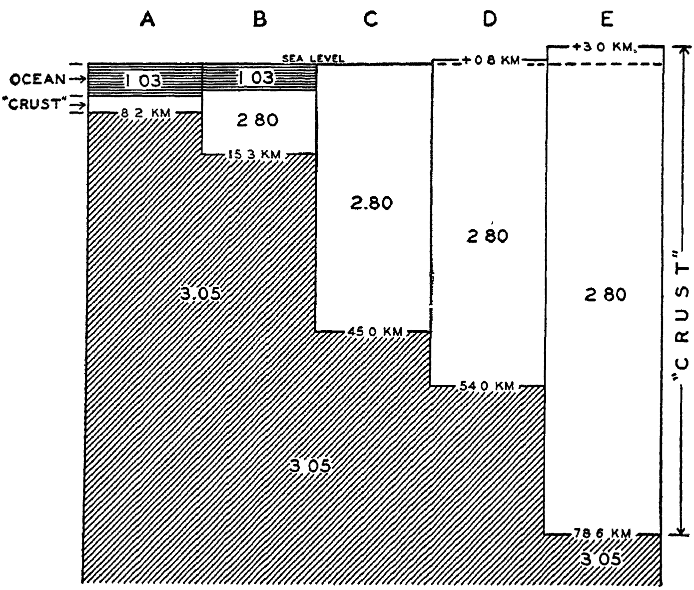

FIG. 88.—Illustrating isostatic equilibrium in sectors *A* to *E* of Fig. 87, according to the Airy explanation of isostasy.

deepest part of the Pacific being 74 kilometers thick. Values of the average densities in sectors C to E and of densities in sectors A and B are indicated. All five sectors are in isostatic equilibrium.

It is seen that the isostatic compensation between any pair of the sectors is concentrated in two loci.

For comparison, Figs. 88 and 89 have been drawn to illustrate the Airy and Pratt hypotheses as affecting the five sectors. The "crust"

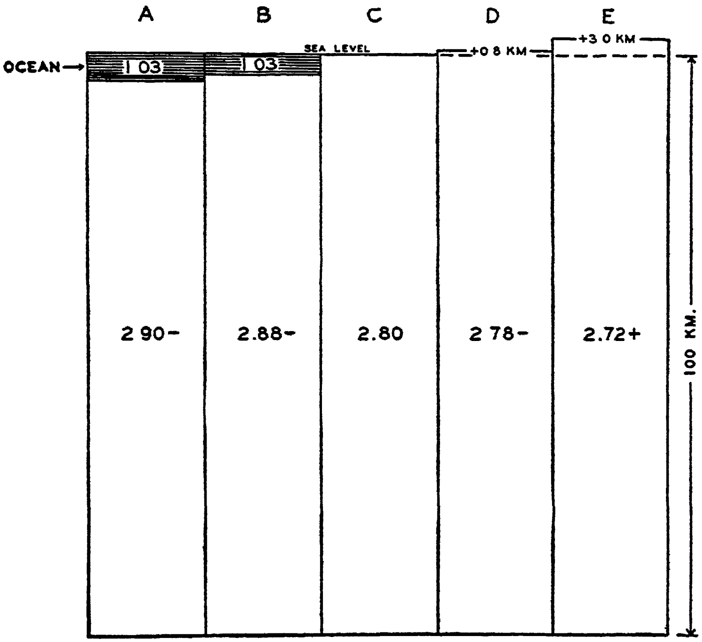

FIG. 89.—Illustrating isostatic equilibrium in sectors *A* to *E* of Fig. 87, according to the Pratt explanation of isostasy.

of the Airy conception (left blank in the drawing) is supposed to have a uniform density. The supporting medium (shaded) is assumed to have a uniform density 0.25 greater. Figure 89 is drawn on the assumption that the mean density of sector C is the same as that of the normal Sial or that attributed to the crust of the Airy hypothesis.

Heiskanen's results show that the arrangement of densities given in Fig. 88 would reduce the gravity anomalies nearly to a minimum, and the effect would be much the same if the arrangement of Fig. 87 were substituted as the basis of calculation. Hence the explanation of isostasy implied by the crust-substratum idea seems to have some support from the pendulum studies so far made.

COMPOSITION OF THE SIAL

The essential nature of the upper part of the Sial may be inferred from recent studies of its chief component, the Basement Complex. Detailed mapping and many reconnaissance surveys show approximate uniformity for the mean composition of the complex, throughout each continent and from continent to continent and larger island. On account of this relative homogeneity in its very heterogeneity, the constitution of the upper part of the Sial can be rather closely estimated from a quantitative study of a single large area of the Basement Complex.

Such a study has been made by Sederholm in Fennoscandia, one of the best-mapped, extensive outcrops of the complex.[1] He measured the Finnish areas occupied by the different kinds of Pre-Cambrian rocks. The results, reduced to percentages of the whole outcrop, are:

Granitic rocks	52.5
Migmatites	21 8
Granulites (leptynites)	4 0
Schists	9 1
Quartzites and sandstones	4 3
Limestones and dolomites	0 1
Basic rocks	8.2
	100 0

Weighting the formations by areas, Sederholm obtained for the complex an average chemical composition, shown in column 1, Table 26. Column 2 gives his average, computed for the Finnish granites. The difference between the two averages is not great. It would be less if the average for the complex had been computed in terms of volumes rather than areas; for the basic rocks are largely effusive and are thin, hence overweighted, when relative areas are used for weighting and a layer 10 or more kilometers thick is to be considered.

A paper by Eskola on the crystalline rocks of Finland contains the following general conclusion (translated): "In the Basement Complex the proportion of granite outcropping increases with the depth of erosion, and at a certain depth the Archean terrane consists of a continuous shell [*Sphäre*] essentially made up of granitic or granodioritic rocks."[2]

Sederholm finds the average rock of the Swedish Pre-Cambrian to resemble closely the average for Finland. In Sweden also, granites

[1] J. J. Sederholm, Bull. 70, Comm. géol. Finlande, Helsinki, 1925.

[2] P. Eskola, Fortschr. der Mineralogie, etc., vol. 11, 1927, p. 106. *Cf.* Min. u. Petr. Mitt., vol. 42, 1932, p. 455.

dominate overwhelmingly and there have a mean composition approximately stated in column 3 of Table 26, which gives (columns 4 and 5) the average analyses of the world's granites and granodiorites, irrespective of age. Lodochnikow emphasizes the essential identity of

TABLE 26.—CHEMICAL AVERAGES OF EXPOSED SIAL IN FINLAND AND OF GRANITES
(Reduced to totals of 100 per cent)

	1	2	3	4	5
SiO_2	67 70	69.42	69 81	70 18	65.01
TiO_2	.41	.39	54	.39	.57
Al_2O_3	14.69	14.70	13 76	14 47	15.94
Fe_2O_3	1 27	1 08	2 17	1.57	1 74
FeO	3 14	2 49	1 87	1 78	2.65
MnO	04	03	26	12	.07
MgO	1.69	2.02	.84	88	1 91
CaO	3.40	1 44	2.20	1 99	4 42
Na_2O	3 07	3 24	3 17	3 48	3 70
K_2O	3.56	4 46	4.38	4 11	2.75
H_2O	.79	66	74	84	1.04
P_2O_5	.11	07	26	19	.20
Rest	.13				

1. Sederholm's average for the complex in Finland.
2. Sederholm's average for the granites of the Finnish complex
3. Average for 114 Pre-Cambrian granites of Sweden (compiled from table of Holmquist).
4. Average for 546 granites of all ages, world-wide distribution (Table 1, column 4).
5. Average of 40 granodiorites (Table 1, column 45).

the petrography of Fennoscandia and of the Pre-Cambrian terrane of Russia.[1] The average rock of the Pre-Cambrian complex of Canada and the United States is nearly the average granite. A similar generalization is highly probable for all other large exposures of the Archean, such as those of Brazil, Antarctica, Australia, Siberia, China, peninsular India, and most of the African continent.

Apparently, therefore, the main mass of the Sial, down to the depth of at least 10 kilometers, has a composition which in most respects is intermediate between granite and granodiorite and also between Sederholm's uncorrected average for the Finnish complex and the average granite of the world. Still deeper the mean composition of the Sial, affected by load metamorphism and by basic intrusions, as well as reflecting ancient magmatic differentiation, probably approximates granodiorite.[2]

[1] W. N. Lodochnikow, Matériaux pour la géologie générale et appliquée, Livr. 69, Comité Géol. Leningrad, 1927, p. 100.

[2] This statement does not conflict with the foregoing conclusion that, to the relatively shallow depths of the Sial exposed by erosion, the proportion of granite increases with depth.

Density of the Sial

The average specific gravity of 155 granites, listed in the 1917 edition of Washington's Tables, is 2.667. On account of the presence of some denser rocks, the Basement Complex near the surface has a density close to 2.70. Metamorphism, basic injections, and probably a slow increase of basic constituents in the original Sialic rock as the depth increases doubtless cooperate in raising the average density to some extent. Even though quartz-bearing all the way to the base of the Sial, the average density of the lower half of this layer may approach 2.90. The average for the Sial as a whole may be reasonably taken to be about 2.80.

The Sima of Continental Sectors

From an early Pre-Cambrian epoch to the present day the Sial has been invaded from below by basaltic magma, now represented by crystallized gabbro, diabase, basalt, greenstones, etc. The degree of chemical uniformity exhibited by this magma directly suggests its primary origin. It can hardly be attributed to differentiation from an intermediate magma just before eruption. The more salic pole of such a hypothetical differentiation ought to have large volume and, being less dense, should normally have been erupted before the basalt. In numberless instances, including the basaltic-plateau regions, such association of more salic magma entirely fails.

We observed in Chapter III that basaltic magma is the only one abundantly represented in each of the larger divisions of the earth's surface. The visible granite is more voluminous than all the visible bodies belonging to the gabbro clan taken together, but the extrusive members of this clan are more evenly spaced on the globe than the extrusive members of the granite clan. The post-Cambrian granites are almost entirely confined to orogenic belts; the post-Cambrian basaltic rocks appear indifferently in mountains, plains, and plateaus, both subaerial and submarine. When magma has been extruded on the largest scale and most rapidly through narrow fissures, where it evidently remained too short a time for the incorporation of foreign material, that magma, ever since Pre-Cambrian time, has been basaltic. Among igneous types, basalts have had the greatest persistence during geological time (see page 42). The gabbro clan is that most steadily represented in the standard eruptive sequences so far described, though probably all such sequences for the continental plateaus, if fully recorded, would include Pre-Cambrian granite.

Some such considerations must have prompted Cotta's assumption of a continuous basaltic shell underlying the visible crust rocks.[1] The

[1] B. Cotta, Geologische Fragen, Freiberg, 1858, p. 76.

same conception was independently attained by W. L. Green, and in 1902 by Daly.[1] All three writers assumed a noncrystalline state for that part of the basaltic substratum from which fluent magmas have been derived. Their hypothesis thus involves two distinct questions: first, as to the horizontal continuity of the deep primary basalt; second, as to the validity of supposing the material to be vitreous. Of course, no answer to either question can be absolutely demonstrated. The only possible outcome of their study consists in the weighing of probabilities—as usual with the fundamental problems of petrogenesis.[2]

The physical continuity of the substratum around the globe is suggested by the facts already briefly described, and also by the behavior of earthquake waves. According to existing information, these waves are propagated in the sub-Sial layer and the corresponding deep suboceanic layer, as if this whole earth shell is horizontally homogeneous to a high degree. For example, below the depth of about 80 kilometers there appear to be no more or less vertical breaks of the kind expected if the earth at these levels were horizontally discontinuous or of what may be called "cellular structure." Though absolute homogeneity of the shell, all around the globe, is hardly to be expected, the assumption of an approach to chemical uniformity along levels has the additional advantages of favoring economy in fundamental postulates and of being consistent with the most probable theory of the earth's origin and early organization (see Chapter X).

Information regarding the physical state of the Sima beneath the Sial is not easily obtained. Great viscosity and high rigidity (against small, periodic stresses) for all the earth's shells down to the depth of about one-half the radius seem definitely proved. Hence a world-circling, fluent "sea of magma" can not be credited. Four other possibilities may be conceived:

a. First, that the sub-Sial layer is holocrystalline with corresponding moderate temperature. This hypothesis automatically accounts for the viscosity and rigidity. On the other hand, neither the eruption of basalt on the large scale nor the demonstrated weakness of the materials at depths little greater than 60 kilometers would find ready explanation.

[1] W. L. Green, Vestiges of a Molten Globe, Honolulu, part 2, 1887, p. 61; R. A. Daly, The Geology of Mount Ascutney, Vermont, Bull. 209, U.S. Geol. Survey, 1903, p. 110. *Cf.* G. Linck, Aufbau des Erdballs, Jena, 1924, and B. Gutenberg in Müller-Pouillet, Handbuch der Physik, Berlin, vol. 5, 1928, p. 670.

[2] J. H. L. Vogt (Skrifter Norske Videns.-Akad. Oslo, Kl. I, 1930, No. 3, p. 5) thought that basalt is effusive on a large scale because of its special fluidity—surely not a satisfying reason. He was opposed to the idea of a great horizontal extension of basaltic material at depth and thus to the assumption of an earth shell of this composition. Vogt did not state his grounds for scepticism.

b. Or that the sub-Sial might be considered as holocrystalline, but during limited fractions of time becoming everywhere molten and notably fluent to some depth. This is the Joly hypothesis of thermal cycles. The next chapter will note the grave physical and geological objections to it.

c. Or that the melting might be assumed to be local and due either to differential radioactivity or to relief of pressure in a limited subcrustal region. Local relief of pressure is hopelessly inadequate and need not be further discussed. We have no evidence for the required local concentration of radioactivity within continental or suboceanic rocks. Since highly fluent basalt is erupted on the floor of the ocean, it would be difficult, on this third hypothesis, to shut out the possibility of complete fusion of a shell beneath the Sial, with its higher proportion of radioactive elements.

An eclogitic composition for a thick earth shell just below layer B (Table 24) has been suggested, largely because its radiothermal or other melting is supposed to give basaltic magma in the required volumes. Yet Bowen has shown that the melting of eclogite, which is not a eutectic mixture, is not likely to give basaltic liquid. Further, the actual eclogites are far from being chemically identical with basalt, as Wagner made clear in one of his last publications. For these and other reasons we may well pause before accepting the idea of a general earth shell of eclogite.[1]

d. The remaining possibility is that selected for present emphasis (see Table 25). Immediately beneath the Sial of normal continental thickness there is supposed to be a layer of crystallized material, chiefly of chemical composition like that of plateau basalt. This layer is assumed to rest upon a layer of amorphous basalt, which since an early Pre-Cambrian epoch has been too hot to crystallize. For convenience the sublayer of vitreous basalt will be designated as the *basaltic substratum.* The substratum and the immediately overlying crystalline sublayer (of dominant piezo-gabbro), taken together, will be called the *basaltic shell* of the earth.[2]

It is first necessary to review the grounds on which, chemically speaking, a basaltic, rather than a peridotitic or pyroxenitic, composition is preferred for the crystalline sublayer.

From the high-pressure modulus of compressibility, Adams and Gibson have computed the velocity of the longitudinal wave in

[1] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 314. P. A. Wagner, South African Jour. Science, vol. 25, 1928, p. 127. Wagner emphasized amphibolite, rather than eclogite, as the probable high-pressure phase of basalt (load metamorphism).

[2] P. Eskola (Min. u. Petr. Mitt., vol. 42, 1932, p. 468) pictures the Sima in much the same way.

plateau basalt, which is assumed to have the chemical composition that had been calculated by the present writer. For the depth of 50 kilometers the velocity found is 7.3 kilometers per second.[1] If the improved average of composition for plateau basalt, given in column 60 of Table 1 be used, the same mode of computation gives a wave velocity of 7.4 kilometers per second at the same depth. According to different seismologists the actual velocity is 7.4 to 7.9 kilometers per second. Even if the material is ordinary unmetamorphosed gabbro, any excess of the wave velocity above 7.4 kilometers per second may, as we have seen, be due to the difference between the static and dynamic moduli of elasticity. The difference may be small and yet more than sufficient to annul the effect of increase of temperature on compressibility. The latter effect is perhaps no greater than the differential effect of compression under the adiabatic conditions of wave transmission as opposed to the isothermal conditions of high-pressure experiments.[2]

Finally, we note that the wave speeds at depths of 40 to 60 kilometers are no greater than they should be if there the material is essentially of basaltic composition but crystallized as some form of piezo-gabbro—an assumption that appears reasonable.

In view of so many possibilities, then, the speeds of seismic waves cannot be said to demonstrate a peridotitic or pyroxenitic layer between the 40-kilometer and 60-kilometer levels, a shell composed of piezo-gabbro, perhaps with some injected ultrabasic material, being more probable.

Basaltic Substratum and Its Physical Properties

Nor do the wave velocities seem to prove crystallinity for a shell beginning at about the 60-kilometer level. At the author's request, Professor Bridgman measured the volume compressibility of Hawaiian tachylite (chemically close to average plateau basalt) through the

[1] L. H. Adams and H. E. Gibson, Proc. Nat. Acad. Sciences, vol. 15, 1929, p. 722.

[2] Concerning the relation of temperature to compressibility, see P. W. Bridgman, Amer. Jour. Science, vol. 7, 1924, p. 363; vol. 10, 1925, p. 488; vol. 15, 1928, p. 292. His more recent experiments (Proc. Amer. Acad. Arts and Sciences, vol. 66, 1931, p. 185) on the volume changes of many liquids under varying pressures agree with earlier experiments in showing a remarkable decrease of the effect of heating on compressibility as the pressure rises. At 10,000 atmospheres or more, the compressibility was in several cases hardly at all affected by a temperature rise of 95°. In any case, if the thermal gradient at the depth of 50 or more kilometers in the earth is as low as geophysicists assume it to be, the temperature effect must be practically negligible compared with the pressure effect.

pressure range of 1 to 12,000 bars (see page 57). At 30° this, like some other glasses, behaved abnormally, the length of the column used actually increasing with rising pressure up to 7500 bars and failing to return to the initial length even at 12,000 bars.[1] The abnormality appears to be confined to low temperatures. At 75° the cause of the abnormality was at least partly removed; at still higher temperature the rate of decrease of cubic compressibility with rising pressure might differ from that calculated. Ignoring this possibility and making the natural assumption that the tachylitic substratum grows more femic with depth, we can make approximate estimates of the compressibilities of the pure glass at depths of 60, 70, and 80 kilometers. From the corresponding densities and the Poisson ratio of 0.27, the value found from earthquake waves, the velocities of the waves at these levels have been computed. The results follow:

Depth, km	Pressure, bars	Volume compressibility	Density	Computed velocity of longitudinal wave, km/sec	"Observed" velocity of longitudinal wave, km/sec
60	17,300	1.13×10^{-6}	2 80	7.4	7.8
70	20,100	1.07	2.82	7.6	7.9
80	23,000	1.00	2 85	7.8	8 0

The wave velocities in vitreous peridotite would probably not be very different. In all these cases the computed velocities are found on the assumption of identity between each seismically effective compressibility and the corresponding static compressibility. If these differ by only 4 to 10 per cent, the computed and "observed" velocities of the longitudinal wave would be nearly the same for each level.

Apparently, therefore, the "observed" velocities of the earthquake waves are not irreconcilable with the assumption that the material below the depth of 60 kilometers in continental sectors is vitreous basalt much like that studied by Bridgman. This remains true,

[1] The volume compressibility of pyrex glass increases with rising pressure, and the same behavior characterizes Ascension Island obsidian, according to P. W. Bridgman, Amer. Jour. Science, vol. 10, 1925, p. 363; *cf.* L. H. Adams and H E. Gibson, Jour. Washington Acad. Sciences, vol. 21, 1931, p. 381.

At room temperature the mean cubic compressibility of tachylite from another Hawaiian flow was found by Adams and Gibson to be 1.45×10^{-6} between 2000 and 12,000 bars and thus about 10 per cent higher than Bridgman obtained for his tachylite at 75°. Since the chemical compositions of the two glasses probably differed but little, the discrepancy is not readily explicable. The apparatus used by Adams and Gibson was not sensitive enough to show the change of compressibility with change of pressure.

even though we have as yet no measure of the small effect of heightened temperature on the compressibility of rock glass.[1]

These various considerations have emboldened the writer to keep his working hypothesis—that there is a change of state near the depth of about 60 kilometers below the earth's surface.

Like hot artificial glass and like pitch at room temperature, the substratum glass is assumed to be extremely weak or even to share the properties of solid and liquid. Against low pressures of relatively brief duration it behaves as an elastic solid, possessing for small periodic stresses marked rigidity—just as a tuning fork made of pitch exhibits rigidity—and possessing high viscosity on account of the pressure, which begins at about 17,000 atmospheres and increases downward. Yet the substratum may have nearly or quite zero strength, yielding indefinitely before even small but enduring stresses in shear and in this respect simulating a viscous liquid.

Two general objections to the idea of a hot vitreous, and therefore weak, substratum, especially when this is regarded as a primary source of post-Archean igneous action, may be noted.

The first objection is founded upon the independence of volcanic vents, opening at different levels and simultaneously active. If the levels of the free surfaces of the lava columns differ by no more than a few scores of meters, there may be no need to doubt the hydrostatic connection of the columns. Explanation by different degrees of vesiculation (net density) is easily possible. Such appears to have been often the case with pairs of vents at the Kilauea sink. Another example has recently been described by Stearns. During one eruption on Mauna Loa "lava was extruded at the same time and from the same fissure on the rim of the caldera, at 13,325 feet above sea level, and on the caldera floor, 300 feet below."[2] But the situation is very different with the simultaneously active Halemaumau and Mokuaweoweo lava lakes of Hawaii, at levels more than 2500 meters apart (Fig. 134). Neither different degrees of vesiculation nor magmatic viscosity can reasonably account for the hydrostatic independence of the two corresponding columns of lava. One must agree with Harker's statement: "The facts warrant us in rejecting decisively the conception of an immediate common stock-reservoir" for the columns.[3] However,

[1] P. W. Bridgman (Proc. Amer. Acad. Arts and Sciences, vol. 67, 1932, p. 1) found that the volume compressibility of each of six different liquids, between the pressures of 11,000 bars and 12,000 bars was smaller at 95° than at 50°, the average decrease for the 45° interval being about 6 per cent (computed from the tables). What is the cause of this unexpected result? It seems improbable that silicate liquids would behave the same way, even at much higher pressures.

[2] H. T. Stearns, Water-supply Paper 616, U.S. Geol. Survey, 1930, pp. 49, 137.

[3] A. Harker, The Natural History of Igneous Rocks, New York, 1909, p. 34.

we have absolutely no definite evidence as to the actual downward extension of either column. The hypothesis that Halemaumau (Kilauea) is the vent of a large, otherwise sealed, liquid injection within the earth's crust—a chamber of laccolithic, lopolithic, or chonolithic character—is sketched in Chapter XV. Its strength is at least as great as the deduction of Harker and others, who have used the hydrostatic independence of adjacent vents to refute the substratum idea; their argument is clearly not conclusive.

The second objection relates to an imagined general instability of the crust, because denser than the substratum. The relatively high density of the suboceanic crust is thereby thought to threaten wholesale foundering. This consequence not being matched by fact, at least since early Pre-Cambrian time, it is argued that the main premise must be wrong.

On the contrary, such catastrophic foundering seems practically impossible as long as the crust preserves considerable thickness—a situation existing ever since the Archean complexes were formed. As stated elsewhere, "Under ordinary conditions deep immersion of any part of the crust cannot take place. Unless the immersion is deep, the strength of the crust is ample to prevent foundering of the partially sunken (downwarped) element."[1] A fuller analysis of the case is given in the writer's "Our Mobile Earth" (New York, 1923, p. 137), where will be found other reasons for the normal stability of the crust. Joly, Jeffreys, Richardson, and Kirsch have come to the same conclusion.[2]

We return to the main theme. Recent studies of hot glass and other liquids make it easier to credit the substratum with all of the three properties—great viscosity, rigidity approaching that of steel, where small periodic stresses are concerned, and zero strength or extremely low strength.

The experiments of Bridgman and others show the viscosity of both crystalloidal and colloidal liquids to rise rapidly with all-sided pressure.

For seventeen out of forty-three pure liquids Bridgman found that the logarithm of the viscosity was "convex toward the pressure axis at high pressure, which means that viscosity increases more rapidly than geometrically

[1] R. A. Daly, Amer. Jour. Science, vol. 5, 1923, p. 364.

[2] J. Joly, The Surface-History of the Earth, Oxford, 1925, p. 106. H. Jeffreys, Gerlands Beitr. z. Geophysik, vol. 18, 1927, p. 12. W. A. Richardson, Geol. Mag., vol. 60, 1923, p. 127. G. Kirsch, Handbuch der Experimentalen Physik, vol. 25, Teil 2, Leipzig, 1931, p. 50.

In the paper cited, Jeffreys points out the fallacy of assuming that the earth cooled all the way to its center because of the foundering of crust blocks.

when pressure increases arithmetically." Eugenol is an example. Even straight-line extrapolation (leading to a minimum value of viscosity at very high pressure) from Bridgman's curve for this substance gives a viscosity of 10^9 at the pressure of 17,000 atmospheres, and 10^{20} at 33,000 atmospheres. If the pressure effect is so great for a decidedly thin oil, we may not be surprised if experiment should indicate for vitreous basalt at 1200° and 17,000 atmospheres a viscosity comparable with that of steel.[1]

That high pressure would endow a basaltic melt with great viscosity is further suggested by Bridgman's explanation of the phenomenon in general. This runs to the effect that the increase of viscosity of a liquid is a high-powered function of the "complexity" of its constituent molecules.[2] Since silicate molecules are much more "complex" than those of liquids on which actual experiments have been made, there seems to be no theoretical objection to explaining the viscosity of the substratum by the pressure upon it.

The rigidities of the earth as a whole and of its constituent shells have been determined chiefly by observations concerning seismic-wave speeds, body tides, and the period of the variation of latitude. In each case the maximum stresses involved are only a few grams per square centimeter—far less than the pressure of one atmosphere. This fact is of prime importance.

Opinions differ as to whether molten glass has any strength. When Feild and Royster measured the viscosities of various molten mixtures of silicates, they found each solution to show rigidity that did not sensibly decay during somewhat prolonged applications of shearing stress, provided that the stress in each instance did not exceed a certain small value. On the other hand, Washburn, Shelton, and Libman found the yield value of molten glasses to be zero; that is, they flow as viscous liquids, not as plastic solids. They wrote: "All strains can be eliminated from glass, which would not be the case if it behaved as a plastic solid." Considering the thermal agitation of the atoms, this view seems the more probable. That the rigidity of the melts studied by Feild and Royster may not mean true strength is suggested by a significant discovery by Adams and Williamson. They published evidence that the time of relaxation of strain in hot glass under small stress varies not inversely as the intensity of the stress (Maxwell's law of elasticoviscosity) but inversely as the square of the stress. Moreover, obsidians of salic lavas commonly, if not generally, exhibit no manifest double refraction in thin section;

[1] Quoted from R. A. Daly, Gerlands Beitr. z. Geophysik, vol. 22, 1929, p. 33. (For brevity a few changes have been made in the reading of the passage.)

[2] P. W. Bridgman, Proc. Amer. Acad. Arts and Sciences, vol. 61, 1926, p. 96.

hence the shearing stresses inevitably generated in flowing rock glass had been largely or wholly annulled even during the limited time of cooling. Thus the melts of Feild and Royster would probably have shown complete disappearance of strain if the time of observation had been longer.[1]

In conclusion, according to the experimental results described, we seem to have two possibilities. The rigidity of the substratum may be either (*a*) permanent against steady but relatively minute stresses, such as those corresponding to tidal and seismic strains; or (*b*), more probably, vanishing as strains of the same order are indefinitely prolonged. In case (*a*) the substratum would be "durovitreous" in the language of Jeffreys, but with an extremely low elastic limit. In case (*b*) the substratum would be "liquevitreous" (elastico-viscous), its time of relaxation under permanent but small stress being measurable in years. Either alternative is consistent with the high rigidity for subcrustal material, as estimated by any geophysical method yet used. Hence the objection of Bowen and others to the idea of a highly rigid, vitreous substratum cannot, in the present state of knowledge, be regarded as fatal.[2] Rigidity is not strength. The pressure on the substratum may cause its material to simulate a more or less perfectly elastic substance, during even the long time (14 months) of stressing as latitude completes its cycle of variation; nevertheless the implied rigidity may decay indefinitely when equally small stresses are applied to the substratum for scores, hundreds, or thousands of years.

Until further experiments on silicate melts at high pressures make the problem clearer, there is indeed risk of making a fundamental error if one assumes a glassy state for the substratum. The sanction for this is in part based upon geophysical speculation, itself not without some support from observed facts, but in large part is based upon evidence of a quite different character—the apparent failure of any

[1] A. Feild and P. H. Royster, Techn. Paper 189, U.S. Bur. Mines, 1918, pp. 11, 33. E. W. Washburn, G. R. Shelton, and E. E. Libman, Bull. Univ. Illinois, vol. 21, No. 33, 1924, pp. 28, 48. L. H. Adams and E. D. Williamson, Jour. Franklin Inst., vol. 190, 1920, pp. 619, 631.

R. Reiger (Annalen d. Physik, vol. 31, 1910, pp. 91, 93) showed that some highly viscous liquids behave like the melts of Feild and Royster, and E. Hatschek (Proc. Roy. Inst. London, vol. 25, Part 2, 1927, p. 245) found the same with colloidal solutions of water. Compare F. T. Trouton and E. S. Andrews (Phil. Mag., vol. 7, 1904, p. 352) regarding the dissipation of strain energy in pitch.

An optical study of *thick* sections of obsidians collected at suitable points along the profiles of glassy lava flows would be of interest in connection with the question of the amount of residual strain in the material.

[2] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 312.

other theory of the earth's constitution to account for the facts of geology and especially petrology.

Among the significant facts is the proved weakness of a thick layer beginning but little lower than the base of the Sial. Even under small shearing forces the material of this layer flows, and the flow brings about widespread isostatic adjustments that correct for previous changes of surface loads, positive and negative. Barrell's argument for considerable strength in the earth shells, down to the depth of more than 400 kilometers, was founded on the erroneous Pratt-Hayford theory of isostasy, as well as on the unproved assumption that correcting flow in depth is not now slowly progressing, and the argument cannot, as it stands, be regarded as convincing.[1]

[1] J. Barrell, Jour. Geol. vol. 23, 1915, p. 44.

Mathematical discussion of gravity anomalies and deflection residuals have led W. Heiskanen and others to assume that the geoidal equator is elliptical. According to the Finnish geodesist (Veroff. Finn. Geodat. Inst., No. 12, 1929, p. 17), the difference of the longest and shortest radii of the equatorial ellipse is 165 ± 57 meters, corresponding to an equatorial ellipse of the solid earth with a radial difference of at least 300 meters This result is not in accord with Heiskanen's general thesis that the earth is in close isostatic adjustment. In a later paper (Gerlands Beitr. z. Geophysik, vol. 36, 1932, pp. 197, 203) he admits that gravity stations are too few to warrant now a definite conclusion as to the ellipticity of the equator, notes that the strong positive anomalies found by Meinesz in the Gulf of Mexico, the Caribbean Sea, and the seas of the East Indies accord ill with the hypothesis of triaxiality, and leaves the question open.

The same number of the journal just cited (p. 242) contains a discussion by A. Prey of the shape of the geoid, supposing isostatic conditions (Pratt type) everywhere. He finds practically perfect circularity for the equator.

F. A. Vening Meinesz (personal communication) doubts that the deduced triaxiality of the geoid is real or anything more than a mathematical abstraction.

On the basis of Heiskanen's earlier and larger estimate of the ellipticity of the equator, H. Jeffreys (Nature, vol. 127, 1931, p. 777) argues for considerable strength in the thick envelope of the earth's core. Further, because the solid moon is observably triaxial, to a degree greater than that expected in a homogeneous body by the distorting effect of the earth's gravitational pull, Jeffreys (The Earth, 2d ed., 1928, p. 229) advances a second reason for doubting zero strength or nearly zero strength for the earth's material between the core and a thin crust. Since his argument hangs on unproved assumptions—homogeneity for the material of the moon, no isostasy within it, and internal temperature sufficient to make the moon's body under unequal load behave like the earth's body under unequal load—the reasoning does not seem conclusive.

Opposed to the idea of considerable strength in the earth's subcrustal material is the fact, repeatedly illustrated in Nature, that the globe has yielded under the small stresses remaining after much of the isostatic adjustment of unloading by regional deglaciation had been accomplished and still continues to yield. Is it possible to reconcile this fact with belief in the earth's triaxiality? Even if demonstrated, would the ellipticity of the geoidal equator represent more than a temporary condition, due to recent geological changes for which the planet's high viscosity still delays complete adjustment?

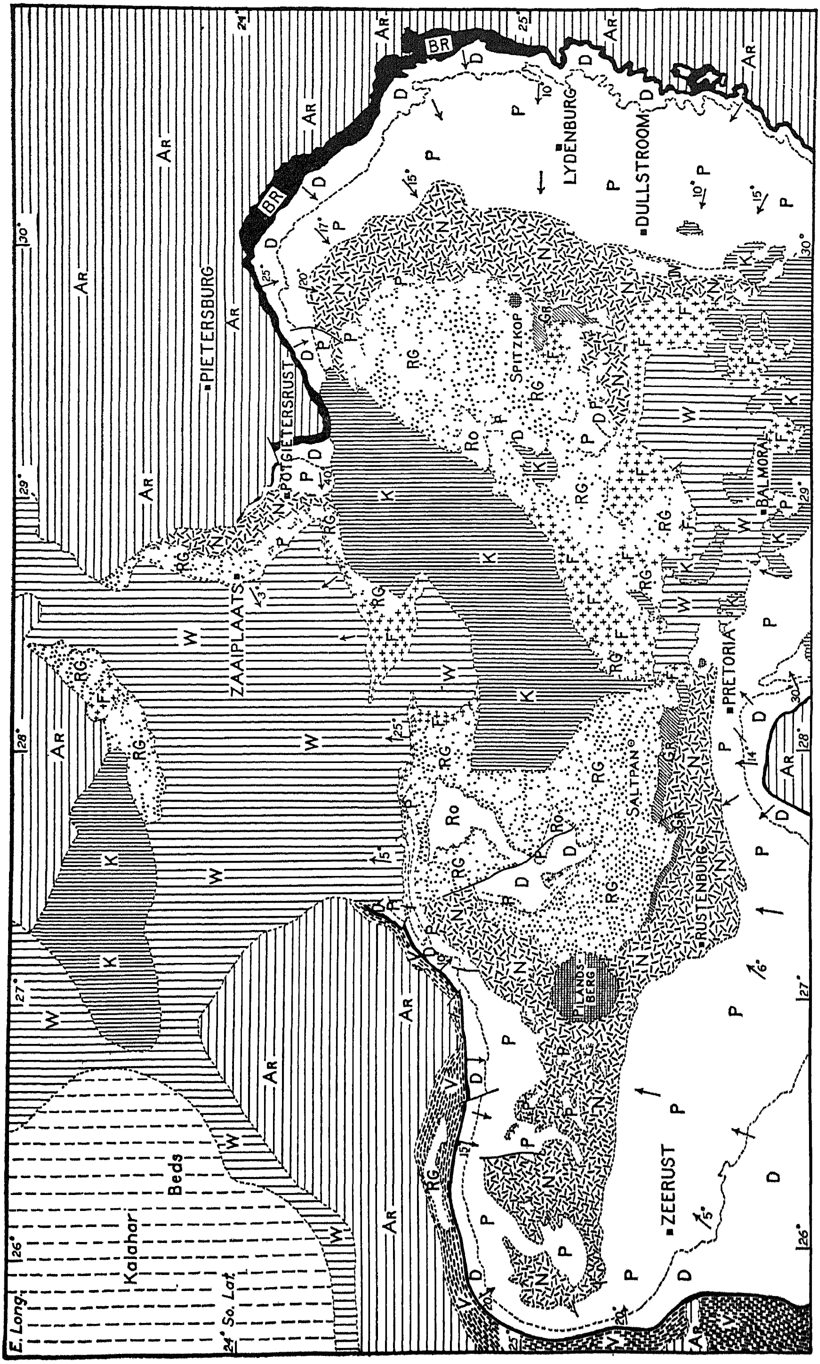

FIG. 90.—See legend on opposite page.

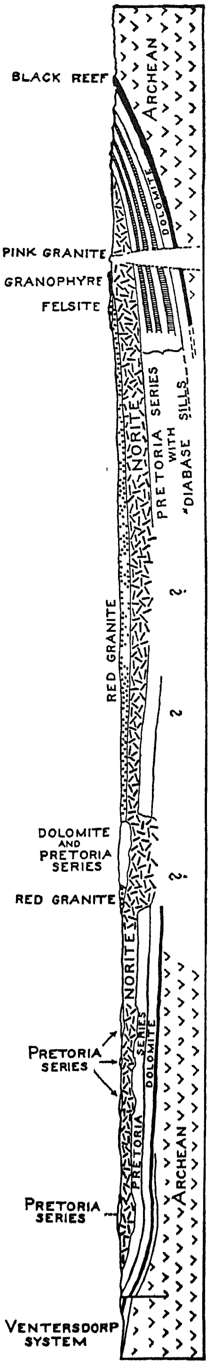

FIG. 90*a*.—Section of the Bushveld Igneous Complex along the parallel of 25° 6' South Latitude (see Fig. 90).

A second evidence of low strength for the earth shell where basaltic magma originates is found in the extensive basining of the Sial under the larger bodies of erupted basaltic rocks. Examples are seen in the Washington-Oregon lava field, in the Deccan plateau, the Minnesota gabbro-basalt field, the Bushveld of the Transvaal (Figs. 90, 90*a*), etc. Each of these eruptions of basaltic magma at major vents involved the flow of the sub-Sial material, even under conditions of low final pressures.

A third evidence is the rapidity of basaltic eruption when the Sial has become charged with throughgoing fissures, distributed over extensive areas. The speed of the eruptions, which continue in spite of the tendency for the narrow fissures to become sealed by the chilling of the lava, indicates great weakness of the basaltic material at the depth of origin.

A fourth evidence is the general, though probably not absolute, restriction of earthquake foci to depths less than 50 kilometers, below which it is doubtful that considerable elastic stress can be accumulated.[1] Much deeper foci of relatively weak earthquakes may be expected if the earth

FIG. 90.—Map of the Bushveld Igneous Complex. Scale, 1:3,000,000. (*From R. A. Daly, Bull. Geol. Soc. America, vol.* 39, 1928, *p.* 710.)

K, Karroo system of sediments, unconformable on *W*.
Cross-hatched, alkaline intrusives of Pilandsberg and Spitzkop.
W, Waterberg system of sediments, unconformable on Bushveld Complex, and on *P—BR*

Bushveld Complex:

- *N*, norite.
- *RG*, coarse red and pink granite.
- *Gr*, granophyre.
- *F*, felsite.

DV, Dullstroom volcanics (basic).

Transvaal system:

- *Ro*, Rooiberg sediments.
- *P*, Pretoria shales and quartzites.
- *D*, Great Dolomite.
- *BR*, Black Reef quartzite.

V, Ventersdorp system, unconformable on *Ar*.
Ar, Archean gneiss, granite, etc.

[1] *Cf.* B. Gutenberg, Handbuch der Geophysik, Berlin, vol. 4, Lief. 1, 1929, p. 233.

has been distorted (as by glacial loading or unloading) at a time so recent that the elastic strain of the deeper shells has not yet had time to disappear. However, seismologists are impressed with the comparative shallowness of most of the determined foci. For example, Jeffreys concludes that the foci of great shocks seem to lie no deeper than 35 kilometers below the surface, and that notable strength is restricted to a shell of the order of 35 kilometers in thickness.[1]

Finally, the multiplying proofs of at least moderate horizontal displacements of the Sial during orogeny seem to demand in explanation extreme weakness for an earth shell at moderate depth. Such low strength in shear can hardly characterize Sialic or any other crystalline material. To assume that the continent-wide shears took place within a vitreous substratum has at least the sanction of making the facts intelligible.[2]

The thickness of the upper, crystallized part of the basaltic shell is not to be easily read out of seismograms. The transition between the crystalline and vitreous basalt might be fairly sharp and yet escape registration by the seismograph, because, at the ruling high pressure, the respective wave velocities would be nearly the same in the two sublayers.[3] Gutenberg suspects a moderate discontinuity under Central Europe at the depth of about 70 kilometers and tentatively regards the change of material as that from "crust" to "substratum."[4] This interesting suggestion needs further study. The calculation of the depth is itself affected by some uncertainty about the depths of the two higher discontinuities already discussed. Gutenberg's depth for the third discontinuity may ultimately be reduced. A depth of 60 kilometers would not be ruled out by the information now available from thermal gradients in the Sial. Koenigsberger places this level where the material passes from crystalline to vitreous at between 50 and 100 kilometers of depth.[5]

[1] H. Jeffreys, Mon. Not. Roy. Astr. Soc., Geophys. Supp., vol. 1, 1928, pp. 518, 521.

[2] The hypothesis of a thoroughly weak substratum seems quite compatible with the fact of peneplanation and with the mechanics of the common warping of peneplains. A discussion of this somewhat complicated set of relations demands too much space to be advisably undertaken on the present occasion.

[3] R. A. Daly, Amer. Jour. Science, vol. 15, 1928, p. 127.

[4] B. Gutenberg, Gerlands Beitr. z. Geophysik, vol. 17, 1927, p. 364; Müller-Pouillet, Handbuch der Physik, vol. 5, 1928, p. 670; Bull. Seism. Soc. America, vol. 21, 1931, p. 216, where also reference to H. Jeffreys' discovery of "a sudden change of the direction of the travel-time curve for *P* waves corresponding to rays having their deepest point at these depths."

[5] J. Koenigsberger, Zeit. f. Geophysik, vol. 5, 1929, p. 295.

Thickness of the Substratum.—Besides the 2900-kilometer discontinuity, Gutenberg records less important breaks at the depths of 1200, 1700, and 2450 kilometers (Fig. 91). S. Mohorovičić found more, apparently less cogent, evidence of others at 120 and 400 kilometers. According to Chapman there is a great and fairly sudden change in the electrical conductivity at the depth of about 250 kilometers, as if there were a discontinuity of material. However,

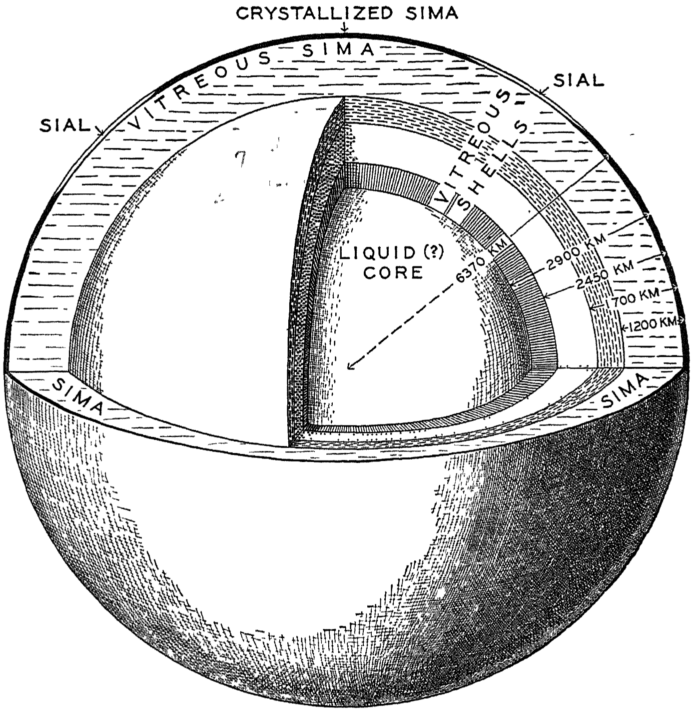

FIG. 91.—Diagram illustrating the shelled nature of the earth. The crystallized Sima below the Sial is thin, thicker elsewhere (heavier exterior line in the sections). Six discontinuities of material are shown, with shell thicknesses nearly to true scale. (*After E. A. Hodgson, Smithsonian Rep. for* 1931, *p.* 358.)

seismologists are not agreed as to the existence of any decided break between the 70-kilometer and 1200-kilometer levels.[1]

Although the substratum is called "basaltic," there is no apparent necessity of believing that its material chemically matches plateau basalt to a depth greater than a few tens of kilometers. *A priori*

[1] B. Gutenberg, Grundlagen der Erdbebenkunde, Berlin, 1927, p. 139; Der Aufbau der Erde, Berlin, 1925, p. 31; Müller-Pouillet, Handbuch der Physik, 11th ed., vol. 5, 1928, p. 751. S. Mohorovičić, Gerlands Beitr. z. Geophysik, vol. 17, 1927, p. 217. S. Chapman, Phil. Trans. Roy. Soc. London, vol. 218, A, 1919, p. 41, and Nature, vol. 123, 1929, p. 229.

we should expect the material to be more femic with increasing depth. Conceivably it approaches the composition of an alkali-poor basalt, such as an oceanite, at a level no deeper than 50 kilometers below the bottom of the crust. The velocities of the earthquake waves do not clearly locate the level of transition into alkali-free peridotite. The thickness of the basaltic substratum thus remains an open question.[1]

Composition of the Substratum.—Has the eruptible part of the substratum, while steadily basaltic in the broad sense since the Archean, changed composition with the march of time? If, in spite of possible temporary thinnings by convection and stoping, the crust has slowly thickened, it is not utterly improbable that the upper sublayer of the substratum was formerly more salic than at present. Was the composition of this sublayer during the late Pre-Cambrian (Keweenawan cycle, Bushveld Complex cycle) directly represented by the quartz diabase (quartz dolerite), granophyric diabase, and quartz gabbro then so abundantly erupted? At a later time was the eruptible sublayer directly represented by olivine-free to olivine-poor basalt, analogous to the Non-porphyritic Central (tholeiitic) type of Mull? Are olivine basalts so common in the Tertiary plateau lavas because, since the Cretaceous period, the eruptible sublayer has been still more femic?

Columns 1 to 4 of Table 27 give the computed compositions of plateau basalts in various regions. The older, Mesozoic New Jersey and Deccan traps are slightly less mafic than the younger, Tertiary traps of the Thulean region.[2]

[1] If comparatively thin vitreous basalt rests upon vitreous peridotite, the discovery of the level or zone of separation between these two layers would be a matter of some delicacy. The speeds of seismic waves in the layers would differ but little, and the existing seismological stations are probably too few and too widely spaced to give the required data.

It is conceivable that convection affecting both the peridotitic glass and the overlying basaltic glass might cause a *temporary* contact of ultrabasic liquid with the solid crust. Thus one might proceed to speculate about the sporadic eruptions of mica peridotite, kimberlite, and even the much greater peridotitic masses exposed in New Caledonia and New Zealand (see Chapter XXII).

[2] In Mull the oldest plateau basalts are of the "tholeiitic" kind and were followed by flows of olivine basalt. W. Q. Kennedy (personal communication) believes it necessary to postulate two parent magmas of these compositions, instead of the one parent, olivine-basalt magma assumed by the authors of the Mull memoir. He does not consider the question of the spatial relations between the two parents before eruption. There is no manifest objection to supposing that the substratum of the epoch was at least locally stratified according to intrinsic density, and that the earlier eruptions more or less exhausted the local supply of the tholeiitic sublayer.

TABLE 27.—AVERAGE ANALYSES OF PLATEAU BASALTS
(Reduced to totals of 100 per cent)[1]

	1	1*a*	2	3	3*a*	4	5	6
Number of analyses	11	6	6	33	7	8	37	43
SiO_2	50 54	49 74	50 01	47 62	46 13	50 68	47 14	48.80
TiO_2	1 91	2.60	2 87	2 72	2 38	1 30	2 44	2.19
Al_2O_3	13 56	12.97	13 75	13 94	15.13	14 29	14.91	13 98
Fe_2O_3	3 19	3 47	2 37	3 59	4.05	3 41	4.11	3 59
FeO	9 91	10.11	11 61	9 41	9 19	8 59	8.22	9 78
MnO	16	.20	24	.22	27	12	.25	.17
MgO	5 45	5 69	4.73	6 81	7.87	6 92	6 91	6 70
CaO	9 44	10 10	8 21	9 86	9 36	8 60	10.01	9.38
Na_2O	2 60	2 27	2 92	2 91	2 22	2 92	2 71	2.59
K_2O	72	.52	1.29	1 01	59	72	.84	.69
H_2O	2 13	2 00	1 22	1 48	2 61	2 28	2 13	1.80
P_2O_5	39	33	78	43	20	17	33	.33

1. Deccan basalts (Washington).
1*a*. Deccan basalts (Holmes)
2. Oregonian basalts (Washington).
3. Thulean basalts (Washington)
3*a* Scottish basalts (Daly)
4. New Jersey basalts (Washington).
5. World plateau basalt (Tyrrell).
6 World plateau basalt (Daly). See column 60, Table 1.

[1] For columns 1, 2, 3, and 4, see H. S Washington, Bull Geol. Soc. America, vol. 33, 1922, p 797; for column 1*a*, A. Holmes and H. F Harwood, Miner Mag., vol. 21, 1928, p. 539; for column 5, G W. Tyrrell, Geol. Mag., vol 58, 1921, p. 497; for column 6, see column 60, Table 1 Column 3*a* gives the average of seven analyses selected by the authors of the Mull memoir as representing the "Plateau Magma type" of the Tertiary province of Scotland.

Mild heterogeneity in the horizontal direction is still another possibility, to account in some degree for the chemical differences among the plateau basalts. Such failure of chemical uniformity might be original or else the result of processes to be later described, namely, convection and major stoping, with temporary thinning of the crust and refusion of the lower, Simatic part of the crust.

Several reasons seem, therefore, to afford some support for the speculation that the composition of the vitreous shell under the continental crust may have had, and may still have, phases varying, from that of an olivine-free basalt to that of an olivine basalt.

Again, it would hardly be astonishing if the substratum beneath the deep ocean were proved to differ chemically somewhat from the substratum of the continental sectors. The sub-Pacific crust is probably thicker than that including the Sial (see page 182). Are the basaltic outflows on the floor of the Pacific so rich in olivine because the top of the feeding substratum there is at a deeper level of the gravitatively stratified shell? If the crust under the other oceans is largely of post-Paleozoic origin and largely represents frozen material from the upper part of the substratum, the residual glass in depth may

be slightly more femic than the top of the substratum in continental sectors (see page 260).

Finally, local downthrusting of the crust (in orogenic belts) well into the stratified substratum might be followed by fissure eruptions tapping sublayers more femic than that normally furnishing plateau basalts.

To summarize: If the eruptible part of the substratum is of variable composition in space and also of variable composition in different sectors of the earth during geological time, the average composition of the substratum may not now be quite like that of the average plateau basalt. Following arguments that involve the use of the latter average should be read in the light of these complicating possibilities.

Suboceanic Shells

Outside the continental slopes the deep, smooth floors of the ocean are interrupted by occasional blocks of the Sial, like the drowned massifs of the Azores, the Seychelles, and the Mid-Atlantic Swell, and by thousands of steep-sided volcanoes. While 30 per cent of the earth's surface is visibly underlain by the Sial, masses of drowned Sial cover an additional total area which may approach 20 per cent of the surface. Throughout the remaining half of the earth, including the middle part of the Pacific basin and much of each of the other ocean basins, the only accessible rocks are volcanic and veneering or interbedded sediments. The dominant lavas of these islands are basaltic; all the remaining types appear to be differentiates of basaltic magma. As above noted, no quartz-bearing rocks of medium or coarse grain, such as characterize the Sial, are found in the volcanic ejectamenta. According to the simplest explanation of these facts, both the eruptible material and the solid rock immediately beneath the oceanic oozes and red clay are chemically of basaltic character.

This conclusion agrees with some seismological observations. Thus, according to Angenheister, the velocities of the longitudinal and transverse waves in the upper part of the sub-Pacific crust are, respectively, about 6.5 to 7.0 kilometers per second and 3.75 kilometers per second.[1] Those velocities correspond well with holocrystalline basalt, gabbro, or diabase. Again, Hiller found for one type of surface waves velocities as follows: 2.87 kilometers per second through Eurasia, 3.58 kilometers per second under the Atlantic, and 3.69 kilometers per second under the Pacific.[2] The difference between the values for

[1] See B. Gutenberg, Handbuch der Geophysik, Berlin, vol. 4, Lief. 1, 1929, p. 240.

[2] W. Hiller, Gerlands Beitr. z. Geophysik, vol. 17, 1927, p. 279.

Eurasia (Sial, with elastic moduli somewhat higher than those of granite at moderate pressure) and the oceanic sectors is just what it should be if the suboceanic crust is chemically a basalt or gabbro. That the velocity under the Atlantic is slightly smaller than that under the Pacific may be readily referred to the proved existence of Sialic rock (probably discontinuous) in the former region.

No thermal gradient has been measured in suboceanic rocks. Hence an important clue to the source of lavas on the sea floor is lacking. If, however, the assumed vitreous substratum under the continents owes a notable part of its temperature to the earth's primitive heat, one naturally suspects that a layer beneath the oceans is also too hot for crystallization. In that case the earth shell of vitreous basalt would be complete, though the thickness of the overlying crystallized layer of the oceanic sectors might be decidedly different from that of the corresponding layer in continental sectors. How different is a question already posed but without speedy answer. The thermal conductivity of Simatic rocks is smaller than that of Sialic rocks; hence a tendency for the crust to thicken faster in continental sectors. On the other hand, the higher radioactivity of Sialic rock probably more than offsets that tendency. Allowing also for isostasy, the author has been bold enough to make a speculative suggestion as to the order of thickness of the crust under the deep open Pacific. The result is embodied in Table 32, page 248.

Needless to say, that estimate, so largely a matter of guesswork, would lose its very basis if the more accessible problem concerning the existence of a vitreous shell under the continents should ultimately be solved in the negative. That the seismologists have not yet been able to identify with assurance a suboceanic discontinuity between crystalline Sima and vitreous Sima does not appear significant when we consider the small difference of wave speeds in the two media.[1]

Densities and the Earth's Moment of Inertia

Assuming Gutenberg's determinations of discontinuities and wave velocities within the earth, Haalck, Gutenberg, and Klussmann have discussed the relation between the distribution of density and the moment of inertia of the planet as a whole. Each of the three supposed the outermost shells to have densities somewhat higher than those here favored. Yet these lower values are compatible with reasonable densities calculated for greater depths so as to give satis-

[1] T. Matuzawa (Bull. Earthq. Research Inst. Tokyo, vol. 6, 1929, p. 229) agrees that the Sial is lacking under the Pacific off Eastern Asia but finds some evidence for a stratified condition for the "crust" in that region; he remarks that the actual uppermost layer may be less than 50 kilometers thick.

factory values for the total moment of inertia and for the mean density. The following table, which bears also Gutenberg's figures for the wave velocities, illustrates the case.[1]

Depth, km	Velocity of longitudinal wave, km/sec	Velocity of transverse wave, km/sec	Density
Crust	5 5–8 0	3 2–4 5	2 9 (average)
60 (vitreous)	7 9	4 4	2 8
100	8 2	4 6	3 0
1200 (above)	12 25	6 75	4 5
1200 (below)	12 25	6 75	5.0
1700	12 50	7 25	5 5
2450	13 25	7 5	6 0
2900 (above)	13 0	7 25	6 5
2900 (below)	8 5		10 5
Center	11 0		12 5

Segregation of the Sial

One of the grandest of all petrogenetic questions relates to the origin of the Sial. Continental lands exist because this light material is concentrated both vertically and horizontally—at or near the surface of the globe and chiefly in one hemisphere. Handbooks of geology and petrology rarely consider the cause; yet no comprehensive theory of the igneous rocks can quite disregard the subject, for in any case the mechanism clearly involved magmatic movements on the biggest scale. An assured solution of this difficult problem is beyond immediate hope. Nevertheless, even a thoroughly speculative treatment will emphasize the organic connection with our subject. First, the mode of the vertical segregation of the primitive Sial will be attacked, and then the intriguing question as to the cause of its present horizontal distribution. The discussion of both problems assumes an initially molten state for the earth, with a cosmogony to correspond—topics treated in the next chapter.

Vertical Segregation.—A picture of the separation of the Sial and the Simatic shell may not be drawn without presupposing a more or less definite composition for their common magmatic parent. On this subject, various suggestions have been made: that the composition was intermediate, specifically andesitic or granodioritic; or peridotitic; or still more femic than peridotite (implied in Kelvin's convection theory of the earth's solidification). None of these ideas is generally accepted, and many more facts must be assembled

[1] Compare W. Haalck's computations, columns B1 and C1 on page 45 of B. Gutenberg, Der Aufbau der Erde, Berlin, 1925, where will be found references to the original papers.

before any well-supported judgment can be reached. The question is tied up with the theory of the origin of the solar system and perhaps especially with that of the moon.

Astronomers have open minds about the moon. The resonance hypothesis of G. H. Darwin has been losing favor with its expert students, who, however, are not as yet able to exclude the possibility that the moon was actually the product of fission from the earth. If the satellite were proved to have this daughter relation and to represent material torn out of an outer shell of the planet, the demonstration would have meaning in the problem of the primitive Sial.[1]

The mean density of the moon is 3.33, of which only about 0.13 can be due to gravitational compression. At the pressure of 1 atmosphere and at 0° C., the moon's material would have a mean density of about 3.20, or 20 per cent higher than that of granite and 7 per cent higher than that of gabbro or diabase, under the same conditions. If the moon was torn out of the earth, and if the earth shell yielding the material was no thicker than 100 kilometers, then that shell would probably not have had the composition of any of our common rocks. A liquid with sufficient silica, alumina, alkalies, etc., to yield Sial and Sima by later differentiation, but carrying an excess of iron, would have the required density. This excess need not have been great if the actual density of the moon is partly due to load metamorphism.[2]

[1] Have cosmogonists pondered sufficiently the possibility that the moon's material was exploded out of the earth when the day was only four or five hours long? There is some evidence that the asteroids are fragments of an exploded planet. Is it out of the question that the infant, liquid earth became charged with gas tension, which, aided by the high rotational velocity at the equator, caused a major disruption? Could the mass have been ejected at an angle with the vertical and with such velocity that much of the mass did not fall back into the planet but remained outside, to ball itself up as the revolving moon?

Or, again, would a similar catastrophe result from the impact of a planetoid with the earth, during the early organization of the solar system? The heat developed by the collision might conceivably prepare the condition for an explosion with the right power and trajectory to separate the lunar mass and the earth.

[2] E. D. Williamson and L. H. Adams (Jour. Washington Acad. Sciences, vol. 13, 1923, p. 419) have shown that pressure alone would increase the density of a homogeneous earth shell from 3.25 to about 4.25 at the depth of 1200 kilometers. According to W. Haalck (see B. Gutenberg, Der Aufbau der Erde, Berlin, 1923, p. 45), such a distribution of density, together with a reasonable distribution of denser materials at greater depth, would give nearly the existing moment of inertia for the earth. However, this fundamental condition would also be met if the existing basaltic shell grows intrinsically denser with increasing depth, perhaps passing into alkali-poor material at a depth not much greater than 100 or 200 kilometers.

Can we exclude the possibility that the moon's mean density was increased by the infall of iron-rich bolides during the final organization of the solar system? It looks as if the impact theory for most of the lunar craters is going to be ultimately

Cosmogonic data, whether referring to the solar system as a whole or merely to the earth-moon system, are manifestly too few to enforce any fixed belief concerning the nature and date of the first terrestrial crust. Neither has geological research given answers to these questions. The oldest known sediments contain free detrital quartz, which was presumably derived from extensive exposures of rock allied to granite, granodiorite, tonalite, or quartz diorite. Doubtless those stratified rocks rested upon a quartz-bearing crust, which, however, may have been the successor of many older crusts, formed and destroyed during the primitive organization of the planet. In any case it is unsafe to postulate a granitic composition for the initial crust. The latter may have been millions of years older than the oldest known granitic rocks. During those millions of years the granitic shell may first have been differentiated.

That already in early Archean time it was so separated from a basaltic layer beneath it is suggested by the vast outpourings of Keewatin, "Katarchean," and correlated basalts upon older terranes of granite, orthogneiss, and quartzose sediments. The conditions leading to the differentiation have been variously described by petrologists, whose views will be further considered briefly in Chapter XIV:

1. Loewinson-Lessing, Sederholm, and Richardson are among those who think the granitic and basaltic shells of magma may have separated because of a kind of "antagonism" between them. Apparently these authors recognize here an effect of liquid immiscibilty, due either to very high temperature or to the presence of much water gas in the original solution.

2. Petrologists of the French school of thought would be likely to explain this major differentiation by the leaching action of magmatic gases, rising from depth and bringing with them the salic constituents of the superficial earth shell. In fact we shall see later that high authorities accept this idea for many early Archean granites, which, being reliquefied by the invasion of gas and heat from below, are batholiths, though not of the same mode of emplacement as the typical post-Cambrian batholiths.

Following the trend of recent petrological thought, one naturally puts in competition the hypothesis of fractional crystallization.

preferred to the theory of gas-controlled eruption from the interior. According to B. Lyot's (Ann. Observ. Paris, section de Meudon, vol. 9, fasc. 1, 1929) elaborate study of the polarization of light at the moon's surface, the material there is like terrestrial volcanic ash; yet similar fragmental deposits would be made by impacts of bolides, so that Lyot's results are not proof of volcanic action in the sense of gas-controlled eruptivity. On the other hand, one need not doubt the possibility of some gas-controlled eruptions on the moon and of lava flooding (areal or fissure eruption) in the broad tracts of the maria.

Accordingly we might assume an original, liquid, superficial, thick (iron-rich?) earth shell containing all the components of Sial and Sima (basalt and some of the underlying ultrabasic material); and a density of the shell uniform enough to permit the sinking of crystals as far as the next layer of distinctly higher density. It seems possible that the fractionation of the superficial layer might lead to the ultimate development of successive sublayers of Sial, plateau basalt, and ultrabasic glass.[1]

Significant in any case is the belief of a number of petrologists in a complete earth shell of basic nature as the source of post-Archean eruptives, either directly or indirectly.[2]

Bowen supposes basaltic liquid to be the direct parent of practically all visible eruptives, and peridotite the probable grandparent, liquid basalt being produced by the selective refusion of solid peridotite. He does not favor the process in reverse—crystal fractionation of vitreous peridotite. His preference for crystallized peridotite is founded upon a conclusion of Adams and Jeffreys, and others, from the "observed" speeds of earthquake waves, a conclusion which we have seen good reason to doubt.[3] It seems incredible that the thick

[1] P. Eskola (Min. u. Petr. Mitt., vol. 42, 1932, p. 459) doubts that the settling of crystals was important in the generation of the primitive Sial and prefers to credit its differentiation to orogenic squeezing-out of acid interstitial liquid from Simatic magma as this was crystallizing. Yet he adds (p. 460): "A gravitative control has nevertheless been in operation: the granitic magma, being lighter than the surrounding rocks, had a tendency to rise." This rise of liquid, as far as it was gravitational, was, of course, relative and was accompanied by the sinking of groups of crystals. Eskola does not directly mention the possibility of squeezing-up by the weight of the crystal mesh, itself denser than the expressed residual liquid. Nor does he adequately discuss the nature of the original solid crust which did the first squeezing; logically it must be assumed to have been not Sialic. Perhaps this difficulty with his theory of the primitive Sial underlies his scepticism (p. 479 of his paper) as to an originally liquid state of the earth.

[2] A. Holmes (Geol. Mag., vol. 64, 1927, p. 264) has suggested that the dominant granite of the visible Sial was differentiated from a superficial layer of liquid granodiorite, the other product of the separation being diorite beneath, while basalt and peridotite formed primary shells still deeper. According to J. H. L. Vogt (Skrifter Norske Videns.-Akad. Oslo, Kl. I, No. 3, 1930, p. 232), the composition of "parental" magma or "presumed average igneous magma" can be calculated from the areas of igneous rocks. He thus found a silica percentage of 65. This method of procedure is at once open to the objection that it ignores the third dimension, depth, of the planet; and there are other reasons why Vogt's result cannot be accepted.

Nevertheless, whatever may have been the first superficial shell, it may have passed through an intermediate state on its way to a dominantly granitic composition at the upper levels.

[3] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 315.

Sialic shell is an extreme differentiate of peridotitic material and yet rests directly upon a peridotitic shell.

The primitive differentiation resulting in the Sialic and basaltic layers may reasonably be thought to have chilled the earth's body only to a moderate depth. The convective interchange of material could hardly fail to decrease the intrinsic (chemically determined) density near the surface and increase it below, so as soon to make impossible the invasion of levels more than a few hundreds of kilometers down by cool foundered crystals or crust blocks. Thereafter the greater part of the planet would be protected against rapid cooling. The "initial" high temperature of the interior, inherited from the gaseous stage, as well as heats of compression and chemical reactions at depth, would be long retained. The heat of deep levels could be transferred to the base of the crust only by the slow processes of conduction and true thermal convection.

Ultimately, however, some of this heat would be transferred and the continued existence of the initial crust threatened. Well before radiothermal action could seriously cooperate, that crust might have been more or less completely remelted. Then would follow a new crusting and a repetition of the story of change.

Further, the profusion of pegmatites in Archean terranes seems to show a "sweating" of the young earth at a rate never approached in post-Archean time. During the early Archean, gases were diffusing upward in special abundance, bringing high temperatures and fluxing power with them. Hence for another reason we are prepared to conceive of wholesale remelting (selective refusion) of the deeper rocks, and that long after the first crust was formed. In the end the upper part of the crust would reach the anchi-eutectic (anchi-cotectic) and essentially stable granitic composition.[1]

The thermal adjustments, like the diffusion of fluxing gases, were slow. Even before the base of the felsic crust underwent its latest remelting, big eruptions of basic lavas from the substratum were poured out at the surface (Keewatin, metabasite type) and thick chemical and clastic sediments had also been deposited. The Sial was beginning its long career towards greater and greater complexity of chemical and structural constitution.

Under the early Archean conditions of a steep thermal gradient and abundance of diffusing gases, the rocks not far below the surface were signally affected by load metamorphism. Systematically flat-lying schistosity was developed in the loaded sediments, volcanic rocks, and plutonic rocks. As late as the close of the Pre-Cambrian, such load metamorphism appears to have made crystalline schists

[1] *Cf.* J. H. L. Vogt, Zeit. deut. geol. Gesell., vol. 33, 1931, p. 193.

out of hydrous sediments that were no more than 6 or 8 kilometers below the surface.[1]

Assuming for the early Archean rocks repeated remelting (palingenesis) and also high fissility, the latter due largely to load metamorphism, we are now prepared to picture great changes in the early felsic crust. Without preliminary eruption of more basic magma, the reborn, gas-rich granitic solutions rose into the upper part of the crust, along fissures and planes of schistosity, whether in orthogneiss, metasediment, or green schist. Millions of thin sheets and lenses of the new granite, aplite, and pegmatite were so injected. With or without associated metasomatism the lit-par-lit solutions froze, with the forms of lens, sill, laccolith, and lopolith. Beneath such a local complex, or beneath one of those other complexes where the granitic liquid invaded steeply dipping older rocks, there may have existed an extensive body of liquid without a floor of crystallized rock—thus a batholith.[2]

There are two possible interpretations of Archean lit-par-lit injections with high dips. Many can be attributed to the mechanism just described, with the additional assumption that the deformations causing the high dips were later than the respective injections. However, we seem to have examples of the reverse time relation. According to Sederholm, Cole, Fenner, and others, post-orogenic invasion of "thin" granitic solutions led, in these cases, to quiet replacement of the deformed rocks. If besides mere metasomatism there was more general fluxing, we have the anatexis of Sederholm and thus palingenetic granites.

[1] See R. A. Daly, Mem. 38, Geol. Survey Canada, 1912, p. 172, with other page references under "Metamorphism" in the Index of the memoir; also Mem. 68, *ibid.*, 1915, p. 44; and Bull. Geol. Soc. America, vol. 28, 1917, p. 400, with references to Milch, Brauns, Dawson, and others.

[2] Writing of the Swedish Archean, P. J. Holmquist (Bull. Geol. Inst. Upsala, vol. 15, 1916, p. 136) stated a general conclusion: The group of older supracrustal formations "subsided in the granite magma and appears on the whole as detached fragments embedded therein. The granites have split up the supercrustal (*sic*) rocks mainly along their own stratigraphical structure-lines and torn away or assimilated unknown masses of layers both on the foot-wall and hanging-wall side of the remaining complex. Only the younger (serarchæan) granites which penetrated the earth-crust in so late a period of the Archæan that the great abyssal granite masses were wholly consolidated, and in some regions also had been strongly metamorphosed, appear independent of the structures of the porphyry-leptite complex. In other words, there are only fragments now visible of that old earth-crust which the great granite masses penetrated, while the crust in which the serarchæan granites were intruded is the same, in the main, as that now existing. It also seems probable that the old granitic magmas never 'erupted' in the usual meaning of the word, but received and enclosed the broken and folded crust-masses as they sank down from the cooling surface."

After prolonged and exceptionally thorough study of the Fenno-scandian Archean, Sederholm is convinced of the remelting of the early granitic crust on a scale quite comparable with that described by Lawson in his classic memoir on the Rainy Lake district.[1] This conclusion is not weakened by the discovery that some of the Archean masses, originally mapped as batholiths, are concordant with the inclosing schists and are really laccoliths or lopoliths.

Horizontal Segregation.—Although tangential forces may have been working earlier, the new felsic crust underwent maximum orogenic deformation at or near the close of the Archean. The cause of this revolution is most obscure. In some respects the deformation seems to have been of the same kind as that registered in the post-Cambrian chains of mountains. These represent thickenings of the Sial, the rocks of which were folded, rafted together, and thus concentrated in the orogenic belts. The new theory of continental migration has suggested that the late Archean revolution might have been due to an analogous crumpling concentration of the felsic crust in one hemisphere. With no other warrant than this analogy, the author has hazarded an application of the "crust-sliding" explanation of orogenic structures in the present problem. According to this speculation, the earth is assumed to have been so distorted as to cause the early Archean Sial to slide, with crumpling pressures downstream, into one hemisphere. There the concentrated and thickened felsic rocks were necessarily in flotation on the earth's body, making possible dry land on the continental scale. In the opposite hemisphere a new, denser basaltic crust was made, as the slow sliding of the felsic crust caused persistent upstream tension and multitudes of eruptions—dikes and flows—from the substratum. When the final isostatic adjustment of levels was completed, a basin covering about half of the planet was ready to receive the primitive ocean.[2]

However, a second hypothesis, founded upon Ampferer's conception of mountain building, itself favored by Schwinner, Bull, Groeber, and Holmes, was also outlined in "Our Mobile Earth" (see page 254). Therewith the Sialic layer, originally covering the whole globe, is assumed to have been dragged on the back of a deep convection current, descending in a region crossed by the equator, and to have been crumpled as the current moved horizontally from one hemisphere to the other.

[1] A. C. Lawson, Ann. Rep. Geol. Survey Canada, 1887, part F.

[2] R. A. Daly, Proc. Amer. Phil. Soc., vol. 64, 1925, p. 283; Our Mobile Earth, New York, 1926, p. 305. Compare A. Wegener, The Origin of Continents and Oceans, London, 1924, p. 150, where Wegener emphasized the great thickening of the Sial through horizontal displacements, though his explanation of the movements is different.

The potential for either sliding or dragging by currents has actually in principle been assigned by Fisher and Pickering to conditions established when the moon was torn out of the earth.[1]

Enough has been said to show that the cause of the chief revolutionary disturbance of the ancient Sial is a matter of practically pure

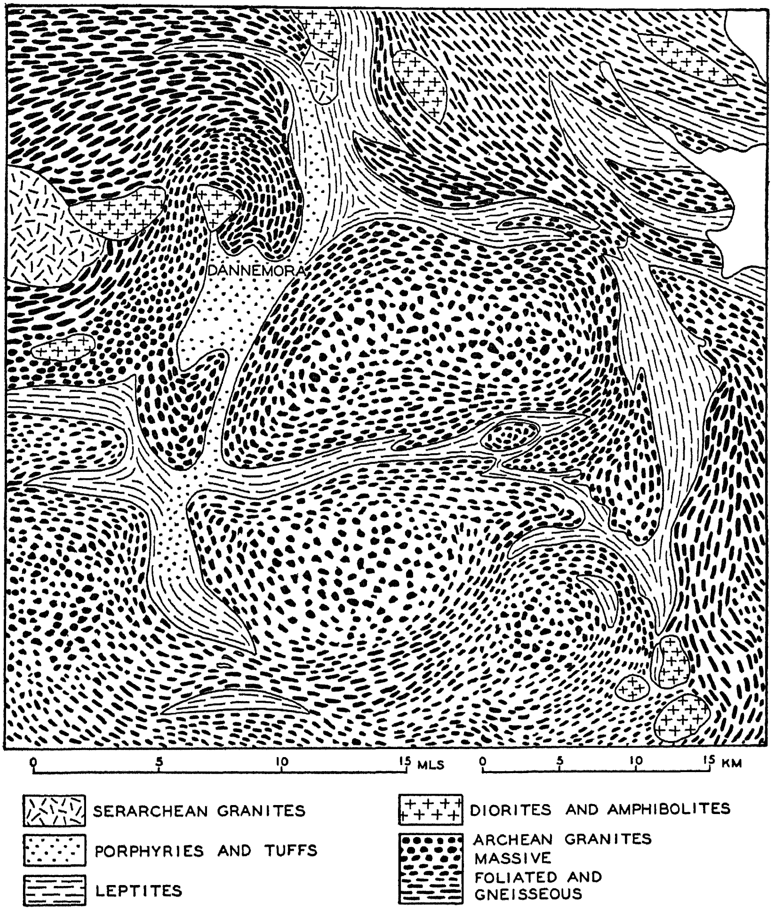

FIG. 92.—Map illustrating the concordant relation of early Archean granites in Sweden. (*After A. G. Högbom, Bull. Geol. Inst. Upsala, vol.* 9, 1909, *p.* 45.)

guesswork, and in this condition the profoundly difficult problem of the earth's asymmetry is likely long to remain. Probably as a direct consequence of the deformation, however caused, the felsic crust, already charged with multitudes of concordant injections, was invaded

[1] See O. Fisher, Physics of the Earth's Crust, 2d ed., London, 1889, p. 338; W. H. Pickering, Jour. Geol., vol. 15, 1907, p. 23, and Geol. Mag., vol. 61, 1924, p. 31.

by big bodies of molten granite. As now exposed, these large younger masses are strongly discordant and without visible bottoms; they are batholiths, according to our definition, and therefore unlike the prevailing injections of the earlier Archean. This structural contrast between the "Laurentian" and "Algoman" types of granitic bodies seems to be as clear as it is widespread (see page 119 and Figs. 92 and 93).[1]

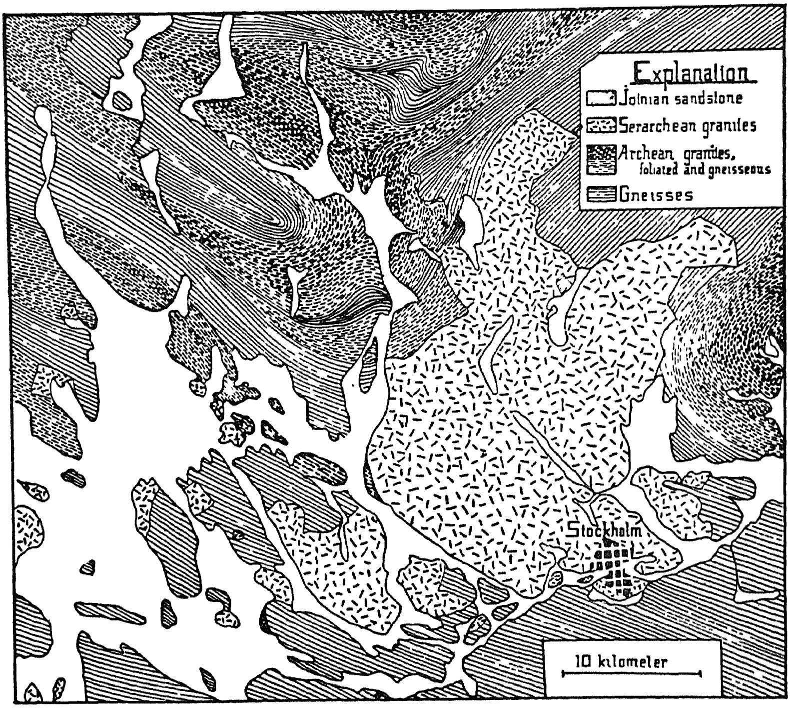

FIG. 93.—Map illustrating the crosscutting quality of late Archean (Serarchean) granites, as contrasted with the commonly concordant granites of the early Archean. (*Copied from A. G. Högbom, Bull. Geol. Inst. Upsala, vol.* 9, 1909, *p.* 26.)

THE CRUST OF THE EARTH

To postulate a vitreous substratum at moderate depth all around the globe is automatically to offer a definition of the "earth's crust":

[1] Like Högbom and Geijer, E. Mäkinen (Bull. Comm. Géol. Finlande, No. 47, 1916, p. 138), studying eastern Fennoscandia, confirms the generalization of Törnebohm when he phrased the described difference in the mode of emplacement of the early and late Archean massifs of granite. Another analogy has recently been brought to light by H. H. Read (The Geology of Central Sutherland, Memoir Geol. Survey Scotland, 1931, p. 194) in northern Scotland, where the Pre-Cambrian lit-par-lit complex involving the Moine schists was developed before the intrusion of the crosscutting, batholithic Helmsdale granite.

the crust is a complete solid-crystalline shell, resting upon a complete noncrystalline shell. The latter has rigidity (for small periodic stresses) surpassing that of granite and is not in the magmatic state as ordinarily conceived. Nevertheless, like the "lava ocean" of the older volcanologists, the substratum retains its latent heat—an additional advantage in supposing it to be the source of igneous action since an early Pre-Cambrian epoch.

The average composition of the crust cannot, of course, be accurately stated. Among the unknown factors are the chemical variation of the Sial in the vertical direction, the thickness of the layer of crystallized basalt beneath, and also the thickness and vertical variation of the crystallized suboceanic layer, described as in general basaltic but differing somewhat from either average plateau basalt or the vitreous basalt below the oceans.

The average of the analyses of igneous rocks does not represent the mean composition of the crust. "Igneous Rocks and Their Origin" contains a discussion of the misuse to which the averages made by Clarke, Washington, and Harker have been put. The later memoir by Clarke and Washington illustrates the obvious truth that weighting for areas and thicknesses is vital.[1] Weighting is the main difficulty and cannot soon be done to general satisfaction. Even then, the average composition of the crust could not be taken to represent the earth's parent magma.

Conclusion

In principle, Table 25, page 178, and Table 32, page 248, give the preferred picture of the existing earth shells. Doubtless it would differ increasingly if imagined for earlier and earlier stages of our planet's history. The primitive state of the earth can be sketched only in highly speculative terms. We have seen that the development of stable shells was a prolonged process. The eruption of voluminous anorthosite is only one of the facts pointing to the contrast of petrogenetic conditions in former times with those ruling at Tertiary and later epochs. It thus seems necessary to allow for secular changes of the earth shells, with corresponding complication for the theory of magmatic origins and igneous eruption through the ages. The existence of crust and vitreous substratum today implies a distribution of temperature to match—the chief topic of the next chapter.

[1] F. W. Clarke and H. S. Washington, Prof. Paper 127, U.S. Geol. Survey, 1924, p. 70.

CHAPTER X

INTERNAL HEAT OF THE EARTH. ORIGIN OF POST-ARCHEAN PRIMARY MAGMA

Introduction

The petrologist has to consider the earth's content of thermal energy and the mode or modes by which "primary" magma has been generated. Primary magma of a given petrogenetic cycle here means the liquid that has not been affected by either differentiation or syntexis (pure melting or assimilation of crust rocks) since the cycle began. Various explanations of primary melts, formed or existing since the Archean era, will be listed, and then a discussion of the earth's heat and allied topics will lead to a statement of the preferred explanation. This preference accords with a conclusion of the last chapter, where it was pointed out that the origin of the Archean rocks and magmas is a problem connected with, but different from, that of post-Archean primary magma.

Origin of Post-Archean Primary Magma

Published ideas regarding the origin of Paleozoic and younger magmas may be tabulated as follows:

A. Hypotheses assuming local isolated bodies of magma in one or more horizontally heterogeneous earth shells. According to different authorities, these "reservoirs" of liquid are supposed to be

1. Inherited from the earth's initial state of complete liquidity (Rosenbusch, Teall, Hopkins).
2. Or caused by relief of pressure, sufficient to produce local liquefaction of crystalline material (Dutton, Harker).
3. Or caused by melting of rock through the friction of its deformation (Mallet, Dana).
4. Or caused by local melting through radioactivity (Holmes, 1915).
5. Or caused by local gas fluxing (Scrope, Day and Shepherd).
6. Or representing "tongues" of liquid (selective solutions), squeezed upward from great depths in the otherwise crystallized earth (T. C. Chamberlin).

B Hypotheses postulating a source of (post-Archean) primary magma in a general more or less homogeneous earth shell, which is

1. Crystalline basaltic or eclogitic and cyclically melted to form a complete earth shell (Joly; Holmes, 1926).

2. Or durovitreous basaltic, becoming liquevitreous by local gas fluxing (Jeffreys).
3. Or basaltic and steadily vitreous except at the top of the shell, where its material has crystallized (Cotta, Fisher, Daly).
4. Or crystalline peridotitic and yielding basaltic liquid by local melting (Bowen).
5. Or liquevitreous peridotitic (Holmes, 1929)

C. Hypotheses postulating sources of primary magma in several more or less homogeneous earth shells, that are or were

1. Crystalline and locally melted (King, Tyrrell).
2. Or liquid throughout (Durocher, von Waltershausen, von Richthofen).

D. Hypotheses postulating two primary magmas without specification of their initial relation to earth shells, these magmas being granitic and basaltic, respectively (Bunsen, Loewinson-Lessing).

Many petrologists have remained agnostic on the subject, partly because of uncertainty about the earth's origin and consequent thermal history. However, the development of cosmogonic theory since 1900 *permits* us to emphasize with new confidence certain fundamental facts of observation. This chapter reviews relevant facts and also current theories of the earth's beginning, as far as these have to do with internal temperatures.

Older speculations about primary magma were summarized by Iddings, but no authority has yet published a full critical discussion of the competing hypotheses.[1] Such treatment is here excluded on account of limitation of space, and yet it is essential to look more fully into the theory of primary magma outlined in the last chapter.

Thermal Gradient at the Earth's Surface

If the earth has a true crust, in the sense of a superficial crystalline layer overlying a vitreous shell, the distribution of temperature must correspond. Any effort to picture this distribution is naturally controlled by the character and meaning of the observed vertical gradients in the crust.

When Kelvin, G. H. Darwin, and other eminent physicists proved the high rigidity of the globe and finally exposed the fallacy of assuming a subcrustal "ocean" of highly mobile magma, many petrologists lost heart in trying to make use of the thermal gradients, measured in tunnels and vertical boreholes. Although petrology is largely occupied with telling of work done at the expense of the earth's internal energy, one of the natural means of estimating the amount of the available energy became suspect. The depth-temperature curves actually demonstrated are short and variable. For more than one reason,

[1] J. P. Iddings, The Origin of Igneous Rocks, Bull. Phil. Soc. Washington, vol. 12, 1892, pp. 89–212; Igneous Rocks, New York, vol. 1, 1909, p. 284.

therefore, the need of caution in extrapolation, even to depths of 50 to 100 kilometers, has long been emphasized. Yet one may well ask if the caution has not been somewhat excessive.

The neglect of the normal gradient as an aid in petrology may be illustrated by a few examples. In his two-volume work on "Igneous Rocks," Iddings ignored the whole subject of observed surface gradients, although he took space[1] to record the highly speculative estimates of Kelvin and Chamberlin for the earth's initial mean gradient to the depth of 300 to 400 kilometers. These estimates were 1°C. per 75 meters of descent and 1° per 1000 meters, respectively. Harker's "Natural History of Igneous Rocks"[2] gives the subject a single paragraph, noting Strutt's guess that the gradient might be wholly due to radioactivity and then adding: "The temperature-gradient merely proves that the Earth is losing heat by conduction outward." Von Wolff[3] realizes more clearly the necessity of considering the gradient in petrogenesis but prefers a seismological method for the discovery of the source of igneous action. On the other hand, in order to interpret the discontinuities found within and just below the Sial, the seismologist needs all the help he can get from the observed thermal gradient. Erdmansdörffer[4] devoted half a page to the subject, quoting the gradient so commonly accepted, namely 3° per 100 meters, and suggesting a possible depth of rock melting at a depth not greatly exceeding 40 kilometers. Tyrrell[5] notes the variation of the gradient both vertically and horizontally. Shand,[6] like Behrend and Berg,[7] does not mention the thermal gradient.

The need of correlating the surface gradient with the temperatures at depths of 25 to 75 kilometers has become more insistent as new information has come from the study of radioactivity in rocks, from seismology, and from the study of isostasy and orogeny. It is therefore appropriate to glance at some of the latest and best determinations of the gradient. For clearness it may be stated that depth is taken as the independent variable and is thus supposed to be plotted as abscissas in the depth-temperature curves. Hence an acceleration in the rate of increase of temperature with increase of depth will be conveniently described as a steepening of the gradient. A flattening of the gradient will mean the reverse relation.

[1] Vol. 1, p. 262.
[2] Page 5.
[3] A. von Wolff, Der Vulkanismus, Stuttgart, vol. 1, 1914, p. 13.
[4] O. H. Erdmannsdörffer, Grundlagen der Petrographie, Stuttgart, 1924, p. 27.
[5] G. W. Tyrrell, The Principles of Petrology, London, 1926, p. 2.
[6] S. J. Shand, Eruptive Rocks, London, 1927.
[7] F. Behrend and G. Berg, Chemische Geologie, Stuttgart, 1927.

Van Orstrand's latest list includes forty-nine gradients, all measured with special care, from the boreholes and mines of Europe, Asia, Africa, Australia, and the two Americas.[1] All but one of their maximum depths exceeded 600 meters, and the majority exceeded 1000 meters. The deepest hole of the list, at Fairmount, West Virginia, measured 2286 meters. Computed averages and certain exceptional gradients of Van Orstrand's compilation are noted in Table 28.

TABLE 28.—RECIPROCAL THERMAL GRADIENTS
(After Van Orstrand)

	Feet per 1°F.	Feet per 1°C.	Meters per 1°C.
Average of 15 gradients in the United States. . .	68 1	122 6	37.3
Average of 19 gradients in Europe	67.6	121.7	37.0
Gradient at Ames, Iowa	140 9	253.6	77.3
Gradient at Calumet, Michigan.	117 4	211.3	64.4
Gradient at Minas Geraes, Brazil	124.8	224.6	68.4
Gradient at Johannesburg, Transvaal (average of 3)................	199 0	358.2	109.2
Gradient in Queensland...	37 2	67.0	20.4
Gradient in South Australia	33 6	60.5	18.4
Gradient at Tuxpam, Mexico.	40 3	72.5	22 1
Average of all 49 gradients...	71 7	129 1	39.3
Average of 47 gradients, rating the average for Johannesburg as one	66 2	119.1	36 3
Average of 46 gradients, excluding the three at Johannesburg.	63 4	114 1	34.8

The average of the 15 (reciprocal) gradients in the United States is 1° per 37.3 meters, and that of 19 European gradients, 1° per 37.0 meters. The author had found the average of 18 British, French, and German gradients to be 1° per 31.7 meters, as against 1° per 41.8 meters for the average of 23 United States gradients, chiefly in West Virginia and Pennsylvania.[2] The considerable contrast between these two averages is to be referred to local, as yet unexplained, conditions.[3] The two averages made from Van Orstrand's table suggest the possibility that there is no essential difference between the average gradients of all Europe and the whole of the United States territory.

The computed crude average of all the gradients in Van Orstrand's list, excluding the very exceptional values for the Johannesburg region, is 1° per 34.8 meters, and thus nearly identical with the gradient commonly assumed as the mean for all the continents. Either

[1] C. E. Van Orstrand, Amer. Jour. Science, vol. 15, 1928, p. 495.

[2] R. A. Daly, Amer. Jour. Science, vol. 5, 1923, p. 352.

[3] Is the contrast connected with the low radioactivity of the granites of Eastern North America as compared with the radioactivity of the granites of Western Europe? *Cf.* Piggot, Table 18, p. 69.

"world" average represents, however, a gradient somewhat steeper than that expected in the Basement Complex, the dominant rock of the Sial. Nearly all of the listed gradients relate to holes sunk in sediments, largely argillaceous and of moderate dips. Argillaceous rocks, especially across their planes of bedding, are poorer conductors of heat than are granites and orthogneisses (see page 61). Since the gradient tends to vary inversely as the conductivity, the average of the measured gradients is probably steeper than the average at the surface of the crystalline Sial.

Significant, therefore, is the gradient in the 1525-meter borehole that penetrated 730 meters of Pre-Cambrian, locally gneissic granite at the Dubbledevlei Farm, north-northwest of Carnarvon, Cape Province, South Africa. This unique case was studied by Krige and Pirow, using highly reliable instruments.[1] The mean gradient found in the overlying horizontal sediments, chiefly shales, is 1° per 24.4 meters. That in the granite beneath is 1° per 45 meters. As Krige and Pirow point out, these two divisions of the gradient correspond well with the values expected when allowance is made for the conductivities of the two kinds of rock. The Carnarvon region has suffered no recent invasion by magma, and it has not been orogenically affected since the Pre-Cambrian. Hence the deepest of all borings, where accurate observations of temperature in the granite of the Basement Complex have been made, is worthy of particular emphasis.[2]

[1] L. J. Krige and H. Pirow, Trans. Geol. Soc. South Africa, June, 1923, p. 50; also H. Pirow, Jour. Chem. Metallurg. and Mining Soc. South Africa, vol. 25, 1924, p. 75.

[2] The low gradient at Johannesburg is not to be readily understood. The mines are sunk in a steeply dipping thick series of quartzites with subordinate other sediments also rich in quartz. If the series has the mean conductivity of a quartz crystal, the observed gradient would imply practically the same rate of heat outflow as that controlling the gradient at Dubbledevlei. V. Rosenstein of the Witwatersand University measured the conductivities of the Dubbledevlei granite and of a "slab" of Rand quartzite, finding respective values of 0.0055 and 0.0092 (personal communication from Dr. L. J. Krige). In accordance with those data, if the rate of flow of heat were the same in the two regions, the gradient at Johannesburg would be 1° per 75 meters instead of the actual 1° per 109 meters. The orientation of the slab with respect to the bedding was not mentioned. If the face of the slab paralleled the bedding, the measured conductivity was smaller than that in the steeply dipping strata of quartzite. Thus it is conceivable that the contrast of the two gradients may be largely explained by the difference of the conductivities. Yet an interesting question remains: Are the Rand mines so cool partly because the surrounding enormous volumes of quartzose sediments have the special poverty in radioactive elements that one expects from the nature of those sediments?

It should be noted, however, that some of the low gradients reported in other parts of the world seem to defy explanation on any basis yet described.

In conclusion, the surface gradient within the upper part of the Sial, which is somewhat more basic and schistose than the South African granite, may be estimated at about 1° per 36 meters, or 28° per kilometer, of descent.

Valid extension of the depth-temperature curve to depths of 40 or more kilometers naturally takes account of several complicating factors.

1. In general, the conductivity of igneous rocks, including orthogneisses, slowly diminishes as the proportion of ferromagnesian constituents increases. If the Sial becomes more mafic as its floor is approached, the gradient, other things being equal, should steepen with increasing depth.

2. Load metamorphism has developed flat-lying schistosity in the Pre-Cambrian terranes on the grand scale, and it is reasonable to suppose that this structure characterizes much of the Sial at depth. Since thermal conductivity across the plane of schistosity is considerably lower than the mean for a given schistose rock (see Table 13, page 61), the actual structure of the deeper Sial tends to give a somewhat steeper thermal gradient than that measured in more superficial and more steeply dipping rocks.

3. Bridgman's experiments show that the conductivity of rocks rises with all-sided pressure; but the rate of rise is so slow that this factor is practically negligible for pressures reaching even 50,000 atmospheres.[1]

4. As a rule, increase of temperature lowers the conductivity of crystalline solids. Up to the temperature of 100°C. (373° Abs.) most of these homogeneous solids on which experiments have been made exhibit conducting power nearly in inverse proportion to the absolute temperature. At higher temperatures the effect of heating on conductivity is not so great, though apparently as a rule it is in the same sense. Bridgman found the conductivity of crystallized basalt to increase as the temperature rose from 30° to 75°. For partly glassy basalt, Poole found it to increase up to the temperature of 200° and then to decrease; between 270° and 600° the conductivity was independent of temperature. With granite, also at atmospheric pressure, Poole noted a decrease of conductivity as the temperature rose from 75° to 537°. The change is to be ascribed partly to the development of cracks in the granite, due to the differential expansion of quartz and other constituents. At 517° the apparent conductivities of granite and (partly glassy) basalt are nearly equal. The result would doubtless have been different if the rocks were under high pressure, so that cracks were kept closed.[2]

[1] P. W. Bridgman, Amer. Jour. Science, vol. 7, 1924, p. 89 (see also p. 62).
[2] H. H. Poole, Phil. Mag., vol. 24, 1912, p. 45; vol. 27, 1914, pp. 58, 81.

5. The conductivity of vitreous rock is decidedly lower than that of the holocrystalline equivalent, but up to the temperature of at least 200° increases with the temperature (see page 62). Hence at the top of a vitreous part of the basaltic earth shell the gradient should be steeper than in the crystallized basalt above, and in the vitreous layer should flatten slowly with increase of depth.

The net effect of these five controls probably causes the gradient to flatten, as depth increases, at a rate smaller than that deducible by the prevailing theory which neglects all five. For this reason the estimates now fashionable appear to make the earth cooler than it really is.

6. We come now to the most troublesome of all the questions affecting the use of the surface gradient in extrapolation to depth. The earth is so old that its crust (outside localities recently subjected to volcanism or mountain building) may be regarded as nearly in the steady state for outflow of heat. If the heat were all primitive, original, the thermal gradient to the depth of 50 kilometers could not deviate much from a straight line; the deviation would be all the smaller because of the controls above listed. If, however, a large part of the heat escaping from the earth is of radioactive origin, the expected departure of the gradient in the lower Sial from a straight line would be considerably greater. Just here the validity of advanced extrapolation from the surface gradient is more affected by uncertainty than it is by our ignorance concerning the actual effects of changes of lithology, pressure, and temperature in depth, all put together. Further discussion of the subject may be fittingly postponed until some of the questions relating to the radioactivity of the rocks are considered. The same questions must be faced before the thermal gradient under the oceans can be even theoretically studied.

Origin of the Earth's Heat

The thermal energy important in petrogenesis is now generally assigned to five sources: the radioactivity of the rocks, the original temperature of the globe, and the subsequent effects of condensation, crystallization, and chemical reactions. The way of the petrologist is hard, for the first of these causes is rooted in the mystery of the atom, the others in the mystery of cosmogony. Their treatment must be speculative, and dogmatism concerning the results of the study is forbidden.[1]

[1] G. H. Darwin (Scientific Papers, Cambridge, Eng., vol. 2, 1908, p. 160) calculated the amount of heat developed in the earth by tidal friction, on the assumptions that his theory of the moon's origin is correct and that the friction occurred in the body of the planet. He found the rate of heat generation to be

Heat of Radioactivity.—Since 1906, when Strutt published his classic paper on the radioactivity of rocks, geologists have felt serious embarrassment in trying to reconcile the history of the planet with its apparent efficiency as a radioactive furnace.[1] This has not been made easier by the discovery that potassium is weakly radioactive, albeit in smaller degree than was at first thought by Holmes and Lawson.[2] If the 40-kilometer Sial has the same radiothermal effect as its dominant rocks have in the laboratory, and if a thick sub-Sial layer is as radioactive as basalt in the laboratory, a stable crust could hardly exist on the earth.

The most widely favored way out of the quandary is to assume rapid decrease of radioactivity with depth, so that the evolution of heat is chiefly confined to a superficial layer of rock at most only a few tens of kilometers thick. The assumption is made in spite of the fact that basalt and other basic rocks, which doubtless have been erupted from depths greater than 40 kilometers, are decidedly radioactive. Different explanations of the rapid decrease of the atomic break-up with increase of depth have been proposed.

1. That pressure or temperature within the earth might keep the atoms from disintegrating was an obvious guess. It was soon found that neither pressure as high as 20,000 atmospheres nor temperatures as high as 1500° affect the radioactivity of radium emanation. Reasoning from analogy and from the general theory of the atom, physicists are now assuming that the break-up of uranium, thorium, and potassium, the true sources of the thermal energy considered, is also not affected by terrestrial pressures and temperatures.

2. Are cosmic rays responsible for the instability of the atoms? If so, radioactivity would in fact be confined to a superficial rock layer, for the "hardest" of these cosmic rays must be so absorbed by the rock as to become ineffective at a very shallow depth.

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at the center, pole, and equator, respectively 3 times, $\frac{1}{2}$, and $\frac{1}{12}$ the average rate. Thus heating by body friction would have been strongly differential. It would raise the average temperature of the globe by many hundreds of degrees. However, H. Jeffreys (The Earth, 2d ed., Cambridge, Eng., 1928, p. 270) has shown reason to doubt Darwin's measure of the tidal heating.

[1] For a good general treatment of the subject, see G. Kirsch, Geologie und Radioaktivität, Vienna, 1928. J. Joly's "Radioactivity and Geology," though older, still holds its place as a valuable work of reference, while furnishing a model of style.

[2] A. Holmes and R. W. Lawson, Phil. Mag., vol. 2, 1926, p. 1218. J. Joly (Nature, vol. 126, 1930, p. 953) quotes experiments showing that potassium is much less radioactive than Holmes and Lawson found. In fact, Holmes now holds (verbal communication) that the original estimate must be reduced by four-fifths to nine-tenths of itself.

In the year 1921, Piccard and Stahel reported on a test of this hypothesis. They found the rate of atomic decay of radium emanation not to be changed by bringing the gas into the Simplon tunnel, where a thick cover of rock screened the specimen from cosmic rays. Similarly negative results were obtained by Compton, using radium emanation in the deep Calumet and Hecla mine, and by Maxwell, using polonium in the zinc mine at Franklin Furnace, New Jersey. These experiments on their face suggest that "ultra-X" rays from an extraterrestrial source do not cause the energetic break-up of uranium, thorium, and potassium. Nevertheless, Dobrouravov, Lukirsky, and Pavlov, who found that the radioactivity of radon was not affected by a cover of 20 feet of water, write:

> It would not be correct, though, on this ground to deny any influence of the rays on radioactive processes. As a matter of fact, the total intensity of the cosmic radiation is so small that it is quite possible that it affects a very minute number of radioactive atoms, and its action cannot be detected, especially in the cases of radioactive atoms of short life. The cosmic rays, furthermore, may perhaps give a start to the disintegration process in the radioactive family and actually cause the disintegration of the first element in the family, for example, uranium. Experiments with this element (observation of the growth of activity of Uranium X) might throw some light on the last question. In this case the total intensity of cosmic rays might be sufficient to account for the radioactive process, as the number of atoms of uranium which disintegrate in unit time is very small.[1]

[1] A. Piccard and E. Stahel, Arch. soc. phys. et nat. Geneva, vol. 3, 1921, p. 542. A. T. Compton, personal communication; L. R. Maxwell, Jour. Franklin Inst., vol. 207, 1929, p. 619. N. Dobrouravov, P. Lukirsky, and V. Pavlov, Nature, vol. 123, 1929, p. 760. *Cf.* J. Perrin, Ann. de Physique, vol. 11, 1919, p. 5; C. S. Wright, Nature, vol. 117, 1926, p. 55; F. Lotze, Nachr. Ges. Wiss. Gottingen, math.-phys. Kl., Heft 1, 1927, p. 84; F. Stober, Chemie der Erde, vol. 6, 1931, p. 368; Anonymous, Nature, vol. 124, 1929, p. 34.

The cosmic rays penetrate rocks to the depth of only a few scores of meters before their energy is practically exhausted. If they are responsible for radioactivity, it is not easy to understand how the lead-uranium ratio for rocks formed at one of the older geological epochs can be so nearly uniform as it appears to be, or why there should be a regular decrease of the ratio with geological age, for screening from the effect of the rays by rock covers should have varied greatly in both space and time. Is this difficulty necessarily fatal? Is it possible that the secondary rays, generated by the impact of cosmic rays on such an element as uranium, bombard other radioactive atoms with energy sufficient to cause the disruption of their nuclei? If so, we might imagine a step-by-step propagation of radioactivity to the depth of a few kilometers. In that case the lead-uranium ratio would tend to approach uniformity in crystals formed during each of the geological epochs. This speculation is prompted by the discovery of Bothe and Becker that, when beryllium is bombarded by alpha particles from the radioactive polonium, new gamma rays, rivaling the cosmic rays in penetrating power, are excited (see Science, vol. 75, No. 1939, 1932, Supp., p. 8).

Evidently, then, the physicists are not yet done with the question, which in principle seems to have been originally raised by Perrin.

3. Kreichgauer suggested that the radioactive atoms are formed from other atoms, exposed to the high pressure and temperature that are developed by the impact of swift meteorites with the earth's atmosphere. This speculation seems to have no appeal for the physicists.[1]

4. In 1915, Holmes ascribed the special radioactivity near the surface partly "to the concentrating action of volatile fluxes." Jeffreys is inclined to favor the idea.[2]

5. Eleven years later Holmes enlarged on another aspect of "gravitational differentiation," merely mentioned in his 1915 paper. Through "crystal stoping" and repeated fusions of crust rocks, the upper, younger rocks were enriched with radioactive constituents at the expense of those older and more deeply seated. He shows, for example, that the abundance of radium, thorium, and potassium in the Finnish granites increases with the decreasing age of the intrusions. The same is true of the granites of Mozambique.[3] However, the data afford no evidence as to the depth below which rocks have thus been rendered practically nonradioactive. This second suggestion of Holmes implies a much greater solubility of uranium, thorium, and potassium in the successive residual liquids than in the corresponding more basic, early formed crystals. Goldschmidt has offered a reason for the differential solubility. Atoms (or ions) of only a certain range of sizes can enter the crystal lattice of the minerals that form early in natural magmas. Hence both the large atoms of uranium and thorium, as well as the small atoms of beryllium and boron do not

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The cosmic-ray hypothesis has a conceivable relation to the history of the geosynclinal prisms. Many of these are of great thickness and of leisurely development. During such a time the Sial, with full thickness steadily retained, was more and more deeply buried under a blanket of poorly conducting material. If the radioactivity of the Sial is undiminished by the burial, the temperature of the earth sector beneath the prism would necessarily tend to rise, the sector expanding vertically. As a matter of fact, the surface of each geosynclinal prism remains low, commonly below sea level, for the scores of millions of years. One explanation of this fact might be found in the bending strength of the crust. However, it could be accounted for also on the assumption that cosmic rays do trigger off the radioactivity of the rocks, for the average sediment is only about one-third as radioactive as the normal Sial and hence the geosynclinal sector would be cooler, more contracted, than the surrounding sectors not blanketed by sediments of importance. It is, however, not very profitable so to speculate until it is shown that cosmic rays have anything to do with radioactivity.

[1] D. Kreichgauer, Die Aequatorfrage in der Geologie, 2d ed., Kaldenkirchen, 1926, p. 295.

[2] A. Holmes, Geol. Mag., vol. 52, 1915, p. 64. H. Jeffreys, *ibid*, vol. 63, 1926, p. 524.

[3] A. Holmes, Geol. Mag., vol. 63, 1926, p. 317.

enter the phenocrystic material. They remain dissolved by the residual liquids. During the crystallization of the originally liquid earth, simple gravity caused the separation of crystals and liquids, with resulting concentration of radioactive atoms near the surface.[1]

6. Joly and Poole also assume surface concentration. In the originally heterogeneous planet the more radioactive materials became heated and expanded more than their surroundings. Because of lower density and because of special mobility, these masses rose toward the surface.[2]

From this brief review of the subject, it is manifest that we are far from a definitive explanation of radioactivity and from proof of the actual law of its distribution within the planet. At present it seems best to accept the prevailing views: (1) The radioactivity of the rocks is spontaneous and not triggered off by cosmic rays or other external agency. (2) The radioactivity lessens with depth below the surface. On that basis the problem of present interest is narrowed down to the question of the rates of decrease of the atomic break-up with increasing depth in the continental and oceanic sectors.

It may be noted at once that any hypothesis postulating the rise of the more radioactive material from depth automatically suggests the possible existence of two maxima of radioactivity at different levels. These would be situated at the top of the Sial and the top of the basaltic substratum, respectively. Accordingly the substratum as a whole would be less radioactive than the plateau basalts, risen from the top of that shell. In this case a simple exponential law of decrease from the surface downward could not be used for calculating temperatures below the crust.

Although assuming decrease of radioactivity with depth, Joly yet believes radiothermal energy to exceed the heat conducted to the earth's surface; as a result the crust cannot attain a steady thermal state. According to his theory of "magmatic cycles," radioactive heating has many times thinned the crust; each thinning permitted the crust to be tidally shifted over the earth's body, whereby the excess heat of the hotter sectors could be rapidly removed by radiation; and therefore the crust grew thicker again, at the expense of a

[1] V. M. Goldschmidt, Die Naturwissenschaften, Jahrg. 18, 1930 (sep.), pp. 10–12.

[2] J. Joly and J. H. L. Poole, Phil. Mag., vol. 3, 1927, p. 1245.

If the revived collision theory of the solar system is correct (see p. 230), may we imagine that the liquid earth, when practically full-bodied, captured radioactive atoms from the "resisting medium" which had derived them from the visiting star? Such atoms would tend to be concentrated near the earth's surface. This speculation might have more weight if it were shown that the solar part of the "ribbon" of collision was nearly or quite devoid of radioactive atoms.

temporary layer of liquid basalt. The generation of magma is thus periodic. His theory led Joly to a new explanation of both orogenic and epeirogenic movements.[1]

Having abandoned his own earlier (1915) position on the subject of the earth's internal temperature, Holmes adhered to Joly's theory, with modifications, for some years.[2]

Adverse criticism of the Joly idea has been published by Jeffreys and by Lotze, both basing their objections upon the principles of physics.[3] Additional troubles, rooted in the facts of geology, have weight. Some of these have been noted by Holmes. Others may here be briefly outlined.

1. The theory demands the swelling of the globe whenever the substratum changes state and therefore expands. Joly assumes periodic stretching of the suboceanic part of the crust and its consequent diking by substratum basalt. This deduction cannot be checked by observation. However, even more pronounced stretching, cracking, and diking of the Sial should have taken place, for the basaltic layer would swell most under the most radioactive rocks of the crust. Now Joly credits post-Cambrian time with several complete cycles of accumulation and discharge of heat; yet great continuous areas of the continents are quite devoid of visible dikes of post-Cambrian age. Moreover, the total volume of the actually observed post-Cambrian dikes, cutting the Sial, is much too small to accord with Joly's estimate of the suboceanic diking.

2. With Bowen we may also question whether the eruptible liquid, formed by the remelting of crystalline basalt, would itself be basaltic.[4]

3. Joly regards the direction of orogenic thrusting in Western America as favoring his theory, but have we any right to assume for the American cordilleras an orogenic mechanism different from that which produced the east-west Alpine and Hercynian (Altaïde) chains? Evidently a hypothesis which admits, as the essential cause of mountain building, a westward displacement of the Sial by tidal action does not account for the east-west chains and for this reason loses a leading argument in support. Moreover, Jeffreys doubts sufficient rapidity for the tidal effect to match the interval of time during which the American cordilleras attained their complex structure.

[1] J. Joly, The Surface-History of the Earth, Oxford, 1925; Phil. Mag., vol. 45, 1923, p. 1167. J. Joly and J. H. J. Poole, Phil. Mag., vol. 3, 1927, p. 1233.

[2] A. Holmes, Geol. Mag., vol. 62, 1925, p. 504, and vol. 63, 1926, p. 306; Phil. Mag., vol. 2, 1926, p. 1231. Later we shall see that Holmes has since discarded the theory of magmatic cycles.

[3] H. Jeffreys, Phil. Mag., vol. 1, 1926, p. 923; Geol. Mag., vol. 63, 1926, p. 516. F. Lotze, Nachr. Ges. Wiss. Göttingen, math.-phys. Kl., 1927, p. 75.

[4] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 312.

4. Joly's hypothesis is founded upon the highly dangerous premise that the earth's present rigidity means crystallinity for the substratum.

In conclusion, while this brilliant attempt to solve the mystery of the quantity of the earth's radioactivity deserves continued attention, Joly's theory does not seem competent to displace the hypothesis that radioactive heating merely delays the process of the earth's continuous cooling. Yet both conceptions face a common difficulty: the power of the radioactive furnace can hardly be estimated until more is known about the store of original heat in the globe.

According to his latest theory of terrestrial heat, Holmes assumes much concentration of the radioactivity in a thin crust and yet enough in the substratum to give a net output of heat greater than that dissipated into space by radiation. The substratum is supposed to extend all the way to the core at the 2900-kilometer level and to be chemically so uniform as to permit convection currents traversing the whole of the thick shell. In the course of time the radioactivity provides a thermal gradient compelling convection currents, rising in certain relatively narrow sectors of the earth, running thousands of kilometers horizontally and just beneath the crust, and then sinking in other narrow sectors. The horizontal currents drag apart the Sialic crust, thus exposing the hot sub-Sial material to rapid radiation; excess heat is removed and the crust is not destroyed by melting.[1]

This hypothesis faces difficulties:

1. Is the 2900-kilometer envelope of the core chemically homogeneous enough to permit the single-step convection? Whatever the mode of the earth's primitive differentiation, it is doubtful that such homogeneity could result. Some leading seismologists locate discontinuities of the second order at the depths of 1200, 1700, and 2450 kilometers, indicating rapid downward increase of density at these levels. Moreover, allowing all that is possible for compression by its own weight, chemical homogeneity for the 2900-kilometer layer seems irreconcilable with the value of the earth's moment of inertia.[2]

2. Like most other authorities, Holmes assumes rapid diminution of radioactivity from the earth's surface down to the level where eruptible basalt originates. Is it not logical to suspect that any radioactivity below the 60-kilometer level also lessens with depth? If it does, and if the earth is heating up rather than cooling, the radioactivity of the thick layer must tend to reverse any thermal gradient that might otherwise favor convection.

[1] A. Holmes, Trans. Geol. Soc. Glasgow, vol. 18, 1929, p. 559; Geol. Mag., vol. 65, 1928, p. 238; Mining Mag., April to June (sep.), 1929, p. 13.

[2] *Cf.* E. D. Williamson and L. H. Adams, Jour. Washington Acad. Sciences, vol. 13, 1923, p. 419, and H. Haalck, Zeit. f. angew. Geophysik, vol. 1, 1927, p. 257.

3. As stated, the hypothesis bears no satisfactory explanation of the loci of rising and sinking currents. Those of the plunging currents are supposed to be indicated by the orogenic belts. Particularly elusive is any cause for the systematic sinking of currents responsible for the intracontinental chains of mountains.

4. The hypothesis provides no adequate mechanism for cooling the Pacific half of the planet, which since Pre-Cambrian time cannot have been exposed to rapid radiation by continental migration. The sub-Pacific crust has manifestly been stable; could it have been stable if the radioactivity of the 2900-kilometer envelope of the core be powerful enough to cause the major convections postulated?

5. Since there seems to have been little rending (tearing-open) of the continental part of the crust from late Pre-Cambrian time to the Jurassic, the temperature of this Sialic sector should, by the hypothesis, have increased for at least half a billion years. With the resulting expansion the Sialic crust should have been stretched and presumably diked. Yet, as we have seen in connection with the Joly hypothesis, extensive continental areas appear to be quite devoid of post-Cambrian dikes of any kind.

Other objections will be noted in the next chapter.

Apparently, therefore, Holmes's courageous attempt to make the facts of geology agree with the assumption that the rate of radioactive heating exceeds the rate of loss by radiation into space is not destined to ready acceptance. Yet his work is of high value as emphasizing the theoretical possibility of thermal convection in the earth. Specifically we shall have to consider the idea that the original, nonradioactive heat of the deep interior has been transferred to high levels by "delayed, tandem" convection (see page 236).

Primitive Heat.—What were the range and distribution of internal temperatures in the newborn earth? How much heat has been lost by radiation? How far has convection aided pure conduction in the wastage of heat? Was the earth ever crusted in a true sense? The answers to these and allied questions, all fundamental for the theory of petrogenesis, imply a rather full understanding of the earth's origin and early condition. Yet cosmogonic theory is almost as speculative as the efficiency of the radioactive furnace and is still unable to demonstrate fully the initial state of the globe. The following brief outline of the more modern theories is intended to illustrate an outstanding conclusion, a negative conclusion: No cosmogonic scheme yet published forbids our assuming a liquid state for the earth when full-bodied. Indeed, according to each of the most recently developed explanations of the solar system (such as the Jeans and Jeffreys tidal hypotheses, and the Jeffreys collision hypoth-

esis of later statement), our planet passed from a gaseous state into a liquid state, and from that to a crusted state. This conception of the primitive evolution seems to furnish a basis for explaining the essential facts of geophysics, general geology, and petrology itself.

Nearly all modern theories agree in holding that the earth's material came out of the sun. The separation of the two bodies has been thought to occur when the sun (1) either flew to pieces (rotational hypotheses of Laplace and Gunn), or (2) was pulled to pieces (tidal hypothesis in general), or (3) was knocked to pieces (collision hypothesis of Bickerton and Jeffreys), or (4) blown to pieces while tidally deformed (Chamberlin and Moulton). In all cases the solar material is assumed to have obeyed the gas laws, so that, for example, the tendency of the hot solar gas to expand was an essential supplementary process. However, on this tendency Jeans and Jeffreys have both laid more emphasis than did Chamberlin and Moulton, who preferred to stress the actual explosiveness of the sun.

The tidal theory, which had been sketched in bare outline by others, was independently imagined by Chamberlin, who enlisted the help of Moulton in its development. Fifteen years ago it had not been adequately considered in any astronomical publication. For no good reason this truly majestic idea was long ignored by all but a handful of specialists in cosmogony. But the geologists were soon spurred to discussion of the new hypothesis, partly because its authors insisted upon the true solidity—crystallinity—of the earth when it had only a small fraction of its present mass and also throughout an assumed prolonged period during which it grew to its present size. Like others the present writer could not see the inevitability of this particular deduction from the tidal theory and, in 1920, pointed out how poorly it accords with some of the facts of geology. The main idea of the theory, the disruption of the sun by a visiting star, has been a fruitful stimulus to investigation and thus has taken its place as a notable contribution to science. Yet the emphasis of Chamberlin and Moulton on the importance of the planetesimal dynamics, with the corollary of a cold earth slowly but greatly growing by the accretion of planetesimals, seemed both unnecessary and misleading.[1] A full listing of the grounds for this conclusion is here not practicable; a few points only will be mentioned.

By the Chamberlin-Moulton version of the tidal theory, the visiting star exerted little more than a trigger effect upon the sun,

[1] See R. A. Daly, The Scientific Monthly, May, 1920, p. 482; W. F. Jones, Amer. Jour. Science, vol. 3, 1922, p. 393; H. F. Reid, *ibid.*, vol. 7, 1924, p. 37; H. Jeffreys, *ibid.*, vol. 9, 1925, p. 395, and The Earth, 2d ed., Cambridge, Eng., 1928, p. 309. The latest authoritative description of Chamberlin's views is to be found in his The Two Solar Families, Chicago, 1928.

the principal cause for the separation of planetary material being the explosive eruptivity of the sun. Hence this explanation of the solar system may be called the *eruptotidal theory*. Because the earth's material was exploded out of the sun, it was supposed to have begun as a condensation of one or more belches of solar gas. Since explosion could deliver belches of many sizes, the way was open to assume that the earth nucleus had mass smaller than the mass of the existing earth. Being so small, this nucleus could not fail soon to liquefy and become crusted. During the succeeding long period of accretion of planetesimals, the earth was supposed to have remained solid at the surface, though heated by increasing self-compression and by chemical reactions among the infallen materials.

However, the eruptotidal theory also permits us to assume the original mass of the earth to have been greater than its present mass. Ejected with an initial (intrasolar) temperature probably much higher than 6000°, the earth belch might well have lost some mass by the escape of high-speed atoms into space but, ever since that reduction, have kept practically its existing amount of substance. According to this variant of the eruptotidal hypothesis, the earth would have been fluid at the beginning of its career, and important growth by the addition of planetesimals becomes a superfluous assumption, even though many solid bolides of solar origin may have fallen into the planet.

Jeffreys, like Jeans, holds the explosiveness of the sun to be now too slight to warrant faith in the dominance of explosion during the formation of the planets.[1] Their version of the theory relies upon tidal force as the essential cause of disruption. The tidally extracted body of solar gas formed a single continuous "filament." Jeans demonstrated the instability of the filament; it would speedily break up and form a number of large gaseous globes—the larger planets. Accordingly, Jeffreys concluded that the earth was at its beginning full-bodied and gaseous, then rapidly liquefied, and finally solidified. The *gas-filament* form of the tidal theory thus implies no significant growth of the planet by accretion of planetesimals. Jeffreys even doubts the former existence of planetesimals in important total mass.[2]

[1] According to Jeffreys, the solar prominences have such small mass that their evidence for any significant eruptivity of the sun at the present time is illusory. In fact, the mass of any prominence is so small that the solar spectrum is little or not at all affected when the spectroscope points directly at the top of the prominence.

[2] J. H. Jeans, Problems of Cosmogony and Stellar Dynamics, Cambridge, Eng., 1919; Nature, vol. 113, 1924, p. 329; The Nebular Hypothesis and Modern Cosmogony, Oxford, 1923. H. Jeffreys, The Earth, 2d ed., Cambridge, Eng., 1928,

In some respects the gas-filament edition of the tidal theory seems superior to the eruptotidal edition. Yet each leaves much to be desired when it comes to a complete explanation of the solar system. Neither accounts adequately for the rotations of the planets or for the great angular momentum of the four major planets, and it is questionable whether either hypothesis satisfactorily explains the low densities of these planets in spite of enormous internal pressures.

Impressed specially by the first of these difficulties, Jeffreys has recently abandoned his own tidal theory and now looks with more favor upon the collision hypothesis of Bickerton. Jeffreys now assumes the matter of planets and satellites to have formed a long ribbon-shaped body of gas, sheared out of the sun by a grazing collision with another star, which, of course, also produced strong tidal deformation of the sun.[1]

The collision hypothesis naturally prompts the query whether much of the material of the planets was captured from the visiting star, for thereby relative velocity would be much diminished and capture of some of the joint ribbon of gas made possible. If the sun did capture such foreign gas in large quantity, the final organization of the solar system must have been a complicated process. The internal motions of the "resisting medium" so generated would be particularly effective in reducing the eccentricities of the initial orbits of the planets. One might imagine that, after the departure of the stellar visitor, there were many collisions among the condensations from the gaseous ribbon. Were the young earth and moon so bombarded? Are the lunar craters souvenirs of that ancient turmoil? Are the low densities of the Jovian family of planets explicable on the hypothesis that these represent, in large part, captured material?[2]

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p. 16; also references given above. Jeans (Nature, vol. 128, 1931, p. 432) does not agree with Jeffreys that the gas-filament form of the tidal theory should be given up, and regards the satellitic systems of Jupiter and Saturn as inexplicable on the collision hypothesis. Jeans accounts for the low densities of the larger planets by assuming that their material was derived from the "topmost" (light) layers of the solar atmosphere.

[1] A. W. Bickerton, Trans. New Zealand Inst., vol. 13, 1880, p. 154; vol. 27, 1894, p. 545; *cf.* A. C. Gifford, New Zealand Jour. Sci. and Techn., vol. 7, 1925, p. 323; Scientia, Milan, September-October, 1932, pp. 141, 203. H. Jeffreys, Mon. Not. Roy. Astr. Soc. London, vol. 89, 1929, pp. 636, 731.

H. Dingle (Nature, vol. 129, 1932, p. 333) has supplied a convenient summary of all the published explanations of the solar system, except those of Hirayama, Van Anda, Gunn, and Berlage.

[2] Essentially the same suggestion, of collision with capture, has been published by C. V. Van Anda (Science, vol. 74, 1931, p. 187) and by K. Hirayama (Proc. Imper. Acad. Japan, vol. 7, No. 5, 1931). Van Anda bases one objection to Jeffreys' collision theory on the improbability that the relative velocity of sun and

Thus the doctors disagree about the origin of our planet. One would be indeed rash if he were to prophesy where collective opinion on this matter will finally settle. Yet it is significant that all of the cosmogonic schemes developed since the year 1900, including the eruptotidal hypothesis of Chamberlin as well as the recently announced hypotheses of Gunn and Berlage, seem fully compatible with the conception of an earth once fluid at the surface.[1]

We may now consider more direct evidence of former fluidity for the earth, furnished by the seismologists. They have demonstrated the shelled structure of the body. Besides the discontinuities found within and just below the Sial and that at the depth of about 2900 kilometers, they at least suspect others at the approximate depths of 1200, 1700, and 2450 kilometers.[2] These rather sudden breaks are continuous round the earth and inclose its core. Nothing short of gravitational differentiation of the materials can well explain such discontinuities. This would mean former fluidity for the earth, however high may have been its viscosity. If, as Oldham, Knott, Visser, Jeffreys, and Gutenberg have suggested, the extinction of transverse seismic waves at depths below 2900 kilometers implies fluidity and high temperature for the core at the present time, the less sceptical should one be regarding former general fluidity.[3] In general, as

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star would be enough to carry the star outside the gravitational net of the sun. Is this objection possibly met by assuming the visitor to have been not much bigger than Jupiter, so that practically the whole of it was captured and now constitutes much of the mass contained in the major planets?

The published tidal theories, like the collisional (all demanding highly elliptical orbits for the planets when first formed), have not satisfactorily explained the approximation of most of those orbits to circularity.

[1] R. Gunn, Jour. Franklin Inst., vol. 213, 1932, p 639; H P. Berlage, Jr., Science, vol. 76, No. 1970, Supp. p. 6.

[2] B. Gutenberg, Grundlagen der Erdbebenkunde, Berlin, 1927, p. 145. H. Jeffreys, Mon. Not. Roy. Astr. Soc., Geophys. Supp., vol. 2, 1931, p. 348; The Earth, 2d ed., Cambridge, Eng., 1929, p. 130.

[3] See especially B. Gutenberg in Müller-Pouillet, Handbuch der Physik, vol. 5, 1928, p. 671. J. B. Macelwane (Bull. Seism. Soc. America, vol. 21, 1931, p. 245) thinks he has found evidence of seismically effective solidity of the earth's core. H. Jeffreys (Mon. Not. Roy. Astr. Soc., Geophys. Supp., vol. 3, 1932, p. 9) shows that the core cannot be a degenerate gas, ionized by the temperature; if fluid at all, it must be a true liquid.

Honda found pure iron to solidify at 1530°, with a volume decrease of 4 4 per cent on crystallization. The latent heat at atmospheric pressure is 33 calories. With these values the Clausius-Clapeyron equation would give a minimum temperature of about 11,000° for the core, if this were composed of iron and if pressure had no effect on the amount of shrinkage with crystallization or on the latent heat. Doubtless none of these conditions is actually represented, but perhaps the computation has some value in suggesting that the core may be really hot enough to behave like a liquid as against earthquake waves.

seismologists continue to "X-ray" the globe, their discoveries will probably help to control thought about its origin.

It seems reasonable to assign much of the gravitational sorting, especially the separation of the "iron" core, to the gaseous stage of the earth's development.[1] Then the central temperatures were high. They became higher as the surface layer was cooled, by radiation, to liquidity, with contraction and consequent enhanced self-compression of the mass as a whole. Further gravitational sorting would be natural during the liquid stage.

Crucial questions arise. How quickly would the liquid earth cool? To what depth would convection be rapid? Simple convection between the iron core and its envelope would be impossible on account of the intrinsic (chemically determined) difference of density. Similarly, if, as Goldschmidt and others have supposed, a thick layer rich in the oxides or sulphides of iron intervenes between the more thoroughly silicate shell and the core, purely convective interchange of heat or material between the two major divisions of the core's envelope would hardly be expected. The extent to which ordinary thermal convection would take place in the silicate shell proper is an important subject for study.

Jeffreys shows that even exceedingly high viscosity could not prevent convection in a chemically homogeneous layer more than 500 kilometers thick; for the viscosity of a liquid layer in which thermal convection begins varies, other things being equal, with the fourth power of the thickness of the layer.[2] Early convective stirring would have tended to produce chemical uniformity of the earth shells, but we seem compelled to assume a decided downward increase of intrinsic density between the 60-kilometer and 2900-kilometer discontinuities—a condition ruling throughout geological time. Initial stirring would probably not chill these outer shells so far as to establish the low thermal gradient theoretically set by viscosity. Since pressure almost certainly accounts for most of the earth's viscosity and since internal pressure was about as high in the young, liquid earth as it is now, thermal convection at great depth must always have been slow. From the surface down to the depth of 100 kilometers more or less, the viscosity of the liquid earth would be comparatively low. Hence a layer of that moderate thickness could be stirred and greatly

[1] See L. De Launay, Comptes Rendus, Acad. Sci. Paris, vol. 138, 1904, p. 712; H. Jeffreys, The Earth, 2d ed., Cambridge, Eng., 1929, p. 29. G. Tammann (Handb. d. experimentalen Physik, vol. 25, Teil 2, 1931, p. 6) has outlined a theory of unmixing of metallic core and shells of sulphide and silicate when the earth was liquid.

[2] H. Jeffreys, The Earth, 2d ed., Cambridge, Eng., 1929, p. 140.

cooled long before the deeper layers were well stirred. Without much delay a solid crust would form out of that superficial layer.

The thermal gradient in the initial crust approximated 1° per 200 to 400 meters, being fixed by the effect of pressure upon the temperature of crystallization. Below the crust the gradient was given by the frankly mysterious conditions of the earth's origin.

After the establishment of a stable crust the surface gradient depended on the subsequent duration of cooling, on the gradient in a thick earth shell beneath the crust, on any convection at *great* depth, and on radioactive heating. The time factor can be roughly stated, but the three other factors are veiled in mystery to an important degree, so that compelling deduction of the existing gradients at depth is now practically impossible. The unknowns outnumber the given equations. Doubt of the actual results of computing the present gradient will be suggested in the following section. Not the least of the uncertainties is that concerning the significance and dating of thermal convection. All of the writers who have made the computations, such as Kelvin, Jeffreys, Holmes, and Adams, assumed early convection, either thermal or material or both, and early stirring of the liquid planet to great depth. Yet clearly we have no assured means of knowing what that depth was.

Temperature of the Crust and Substratum

For petrology, the temperature of a superficial earth shell of the order of 100 kilometers in thickness is the most vital problem connected with the thermal energy of the globe. Because the relative importance of original heat, the heat of self-compression, the heat of delayed chemical reactions, tidally generated heat, the heat transferred upward by convection, and the heat due to radioactivity remains unknown, the gradient of that shell cannot now be satisfactorily deduced by mathematical methods. Nevertheless, the efforts of Holmes, Jeffreys, and Adams to compute the temperatures at moderate depths within the earth have had suggestive results.[1] In principle, all three writers made the same fundamental assumptions regarding the initial distribution of temperature and regarding the loci of radioactive heating. Possible heating of the interior by chemical reactions taking place after the original crusting and—a more important question, just noted—possible convective overturn of the earth shells during geological time were ignored.

[1] A. Holmes, Geol. Mag., vol. 52, 1915, p 111. H. Jeffreys, The Earth, 2d ed., Cambridge, Eng., 1929, p. 154. L. H. Adams, Jour. Washington Acad. Sciences, vol. 14, 1924, p. 459.

The gradient deduced by Holmes comes nearest to that which seems plausible; it is here reproduced (Table 29).

TABLE 29.—CALCULATED THERMAL GRADIENT IN THE EARTH*

Depth, km	Temperature due to primitive heat, °C.	Temperature due to radioactivity, °C.	Total temperature, °C.
10	79	264	343
20	159	441	600
30	240	560	800
40	318	640	958
50	396	692	1088
60	479	727	1206
70	555	752	1307
80	634	768	1402
90	713	778	1491
100	790	785	1575

* A. Holmes.

At the depth of 60 kilometers the pressure is about 17,000 atmospheres. This pressure raises the temperature of crystallization of basalt, perhaps as much as 200°. The Holmes gradient permits the assumption that under the continents basalt could not crystallize at depths greater than 75 kilometers. The gradients computed by Adams and Jeffreys are less steep and would forbid belief in a substratum of vitreous basalt at any depth less than 200 kilometers. But all three depth-temperature curves would be significantly changed if only moderate changes were made in the coefficients used for the calculations. Though treated as constants, the coefficients to be correctly employed are all variable quantities. If the computation took account of these variations, the effect of the improvement would be to give a hotter earth. Again, the conductivity and diffusivity actually assumed were taken from experimental results on crystalline rock. This procedure comes close to a case of begging the question. Suppose, for example, that the thick, essentially basic earth shell chiefly involved was initially vitreous and remained largely in that state for much of geological time; then the mean conductivity and specific heat should, respectively, be taken as nearer 0.003 and 0.35 (c.g.s. units) than the 0.004 and 0.20 assumed by Jeffreys.[1] Cor-

[1] Some obsidians show measured conductivity (k) no greater than one-third that of granite. See K. Schulz (Fortschr. der Mineralogie, 1924, p. 378), with reference also to Koenigsberger and Mühlberg, who found k for Lipari obsidian to be 0.0019, while k for the nearly chemical equivalent, granite, averages about 0.008. Increase of temperature seems to increase k in vitreous substances, but only very slowly.

J. H. L. Vogt (Die Silikatschmelzlösungen, Oslo, part 2, 1904, pp. 45, 48) shows that diabase or basalt at the melting temperature has a specific heat of nearly 0.35, and that the specific heat increases with some rapidity as the tempera-

respondingly, the mean diffusivity would be about half that assumed by Jeffreys.

If the preferable, or at least reasonably competing, estimates of the "constants" are used, along with Jeffreys' values for the age of the earth and for the thickness of the radioactive layer, the calculated contribution of radioactivity to the existing thermal gradient comes out smaller, and the gradient considerably steeper, than those computed by either Jeffreys or Adams.

Finally, we see another, even more serious uncertainty in the problem—the value of the quantity that should correspond to what has been taken in the various calculations as the "initial" gradient in the planet. All three calculations were made on the supposition that this gradient was established by the relation between pressure and the melting temperature (solution temperature) of a chemically uniform material constituting the envelope about the relatively small iron core. That postulate implies thorough convective mixing in the envelope while the earth was liquid at the surface. However, we have already noted the probability that not only had the core been segregated by differential density and gravity, but that the envelope of the core was itself early stratified according to intrinsic (chemically determined) density.[1] In that case unbroken or *single-step* interchange of material and heat between top and bottom of the envelope might be impossible. The actual convective cooling of the deep sublayers would be slow: first, because of the comparative thinness of each sublayer; second, because of the high viscosity produced by pressure, even at an early stage of the earth's history; third, because transfer of heat from each underlying sublayer of the envelope to the sublayer above it, or from the dense core to the envelope as a whole, could take place only by the slow process of conduction.

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ture of the melted rock rises. R. B. Sosman (The Properties of Silica, New York, 1927, p. 314) describes similar increase of the specific heat of vitreous silica as it is heated. W. P. White (Amer. Jour. Science, vol. 47, 1919, p. 19) found analogous behavior by each of many silicates (see p. 63).

[1] H. Jeffreys (Mon. Not. Roy. Astr. Soc., Geophys. Supp., vol. 3, 1932, p. 7) has recently concluded that the 2900-kilometer "rocky shell" of the earth was by pressure "solidified from the bottom upwards in the earth's infancy." The initial temperature of the young, liquid planet is thereby supposed to have been low enough for hydrostatic pressure to freeze the whole shell. This fundamental assumption can hardly be regarded as proved.

If the earth's core is without rigidity, it may be important in petrological theory for a reason other than that it is a reservoir of heat. In the next chapter we shall see that the tensions leading to magmatic eruption may depend upon the distortion of the earth's body, a process perhaps partly controlled by the mobility of the heart of the globe.

Greatly delayed, *step-by-step*, or what may be called *tandem* convection, operating at widely separated intervals throughout geological time, thus seems more probable than single-step convection operating from center to surface or from base to top of the silicate shell.

Again, we may recall deductions sketched in the last chapter. As the first complete crust was being formed, the denser, early-formed crystals sank, to be resorbed in the hot, lower sublayers, and residual liquids rose. Hence there was further weakening of the density gradient on which the thermal convection of the young earth depended. We have imagined that under the circumstances a number of crusts were destroyed by this leisurely overturning and cooling of the more superficial part of the silicate shell—a process perhaps occupying millions of years. With each crusting and fractionation, the intrinsic density of the lower sublayers would be increased, and at last thermal convection would cease. Its resumption would be long *delayed*, until slow conduction of heat at the appropriate discontinuity or discontinuities had restored the thermal gradient sufficiently.

If such "tandem" convection with the underlying postulate of zero strength for the deeper earth shells be assumed, it follows that the amount of original heat to be dissipated during geological time would not be measured merely by the "initial" surface temperature and an "initial" gradient of temperature near the earth's surface, as in all the mathematical discussions so far published. Calculation of the existing gradient in depth would give a quite different result from that postulating an initially fixed quantity of heat in the outer 500-kilometer layer. Within that layer, cooling would steepen the gradient at first, but after a long period of time convection would restore the gradient there to something like its original value. Successive coolings and intermittent convective overturns would give higher temperatures within the 500-kilometer layer at the present epoch than those computed for an earth unaffected by convection during geological time.

Speculative as all this is, we can hardly avoid one conclusion: where the amount and dating of convection, the efficiency of the radioactive furnace, and so many other unknown factors are to be considered, final judgment in the matter must be long postponed. Evidently none of the published mathematical analyses is well enough based in these respects to prevent belief in an existing thermal gradient so steep as to imply a vitreous condition for a basaltic shell at moderate depth in the earth.

Perhaps seismology is able to furnish useful evidence. If the Sialic quartz inverts from the low to the high form at a given level, there must be a sudden change of the elasticity of the rock at that

depth. Locating this discontinuity by seismological methods would give the datum for computing with fair exactness the temperature at this rather deep level. The result would be a great extension of the measured thermal gradient in the upper part of the Sial. Elsewhere the writer has published the query whether the discontinuity, placed by Gutenberg at about 30 kilometers below the surface of Central Europe, is to be thus explained.[1] According to Gibson's experiments at pressures up to about 3000 bars, pressure raises the inversion point of quartz at the mean rate of 23.2° per 1000 bars. If the inversion takes place at depth of 30 kilometers, the temperature there is about 760°. The mean increase of temperature to that depth in the Sial would be 25° per kilometer or 1° per 40 meters. Needless to say, little stress should be laid on this highly speculative idea.

When Gutenberg tentatively located the slight discontinuity corresponding to the top of the substratum at the 70-kilometer level, he based his estimate on certain values for the thicknesses of the shells and for wave velocities. All of these values have since been somewhat changed, with the result that the discontinuity in question might be expected to be a little higher. If the depth is 60 kilometers, the temperature of melting for basalt is 1150°, and the rate of the raising of that temperature is 3° per kilometer, the temperature at the 60-kilometer level is 1330°.

TABLE 30

Depth, km	1 Present hypothesis	2 Holmes	3 Adams
Approximate temperatures at:			
0	10°	10°	10°
30	760	800	630
60	1330	1206	960
Approximate gradients at:			
0	28°/km	38°/km	35°/km
30	22 /km	18 /km	15 /km
60	16 /km	11 /km	10 /km

Combining these speculative results with the best value of the surface gradient in the normal crystalline Sial, we have column 1 of Table 30 indicating the present temperatures and gradients reasonably assumed as ruling within a continental sector. Columns 2 and 3 give the corresponding figures calculated by Holmes and Adams.[2]

[1] R. A. Daly, Amer. Jour. Science, vol. 15, 1928, p. 130; Bull. Seism. Soc. America, vol. 20, 1930, p. 49. See also B. Gutenberg (Handbuch der Geophysik, Berlin, vol. 3, Lief. 1, 1930, p. 458).

[2] The values of column 1 are to be preferred to those stated on p. 50, Bull. Seism. Soc. America, vol. 20, 1930.

The table has been compiled not, of course, to express anything like accurate knowledge of thermal conditions within the earth's crust, but to illustrate in principle the mathematical consequences of hypotheses. Column 1 is little more than a restatement of the author's hypothesis of crust and basaltic substratum. Column 2 implies vitreous rock at a somewhat greater depth. According to Adams, column 3 gives values consistent with the idea of a holocrystalline earth, and yet we have seen how insecure, if not decidedly improbable, are the assumptions on which the mathematics are based. The values of column 1 seem admissible on geophysical grounds, but that they even approximately represent the true relations of temperature will long defy direct proof. The practical question remains: Do these values, or values not widely different, agree best with the myriad facts of igneous and general geology?

Lacking measurements of the thermal gradient below the oceans, we meet still greater troubles in estimating the depth where temperature prevents crystallization within the oceanic sectors of the earth. If all of the emanating heat were original, the continental part of the crust would be thicker nearly in proportion to the higher conductivity of the Sial as compared with the Simatic suboceanic crust. We saw in the last chapter that greater radioactivity of the Sial tends to make the continental part of the crust thinner than the suboceanic part. The strength of this tendency cannot be measured until we know more about the distribution of the radioactive elements. As Holmes has noted, the average rock of the Sial, is for two reasons, probably much less radioactive than "average granite." In the first place, the bulkiest granites at the surface are those of the Pre-Cambrian and seem to be only about one-half as radioactive as average granite.[1] Second, it is reasonable to suppose that the Sialic rocks become somewhat more basic and less radioactive with increasing depth. If the decrease of radioactivity with depth is faster in the Sial than in the suboceanic crust, the heating of the different sectors would tend toward a uniform rate; for the temperatures thus produced at depth vary nearly in inverse ratio to the square of the rate of decrease of radioactivity with depth.[2]

It seems, then, possible that the crust may be no more than 20 kilometers thicker under the ocean than under a continent of normal elevation (compare Table 32, page 248).

[1] See A. Holmes, Geol. Mag., vol. 62, 1925, pp. 509, 533; J. Joly and J. H. J. Poole, Phil. Mag., vol. 3, 1927, p. 1239. Holmes (*op. cit.*, p. 533) has even suggested that the Sial under high Asia may have an average content of radium no higher than Joly and Poole have found in average basalt.

[2] See equation (9) in A. Holmes, Geol. Mag., vol. 52, 1915, p. 60.

If, say, one-half of the surface gradient is due to radioactivity, the curve must flatten considerably as it is followed down to the depth of 100 kilometers.

Conclusion

The problem of the heat of the earth is seen to be particularly elusive. Among the preliminary questions to be answered are: the real meaning of the measured thermal gradients, the values of radio-thermal action at all depths, the cause and amount of the earth's nonradioactive heat, and therewith the origin of the planet itself. Not one of the published answers is final or universally admitted. At this vital point, petrology and general geology can do no better than balance probabilities. Nevertheless, the problem is not a matter of pure uncontrolled guesswork. Sanction for the solution implied by the crust-substratum idea is both negative and positive. This chapter attempts to show that cosmogony and geophysics do not automatically exclude the idea, which, as succeeding chapters will illustrate, appears to furnish a reasonable basis for an explanation of the igneous rocks.

Thus it is assumed (1) that the earth is slowly cooling in spite of the radioactivity, so largely concentrated near the surface; (2) that the silicate layer is nowhere crystallized to a depth much below the 80-kilometer level; (3) that beneath the crystallized crust is a succession of vitreous shells, with intrinsic density increasing as depth increases, and a specially dense core at the center; (4) that thermal convection is perhaps possible in each of the thicker earth shells, the transfer of heat from great depth being of the intermittent, step-by-step, or tandem kind; (5) that such delayed convection may be partly responsible for the relatively high temperature of the outermost shells, notwithstanding the earth's age and its limited radioactivity; and (6) that primitive heat has been at least as important as radioactivity in establishing the thermal gradient at the surface of the globe, and in supplying the heat that through the ages has been dissipated into space.

CHAPTER XI

ABYSSAL INJECTION

Introduction. Legato and Staccato Injection

The conception of crust and vitreous Simatic substratum cannot, of course, be directly verified. Like all other ideas concerning the earth's interior, it is to be tested only in a roundabout way. If true, the petrological and geological facts, known and to be discovered, should be found to agree with it. A leading purpose of this book is to outline such a test, in relation to the mechanism of magmatic eruption and to the formation of individual bodies of igneous rocks. The vitreous substratum is thought to be the principal source of magmatic energy as well as the source of much magmatic material since a comparatively early Pre-Cambrian epoch, and itself to have been separated from the primitive Sial before that epoch. The degree of correspondence of the crust-substratum hypothesis with the petrogenetic events of later periods will now claim attention.

Since the accessible part of the crust is essentially Sialic, rocks belonging to the gabbro clan, all derivatives of basaltic liquid, are clearly exotic where they are visible. The crust under much of the deeper part of the ocean appears to belong to the Sima, but there also the visible rocks of basaltic composition were erupted through at least the upper part of the crust. Much more speculative is the statement that these eruptives were once part of, and have risen from, the substratum. According to our general theory, they seem best interpreted as due to *abyssal injection* of substratum material along *abyssal fissures* in the crust. The injection, like the fissuring, is called "abyssal" (Greek *abyssos*, bottomless) in order to emphasize its beginning in depth and also the lack of a crystalline floor for the filling of the fissure.

To be distinguished are secondary fracturing and injection, represented, for example, by many sills, laccoliths, etc., that were injected from magmatic chambers already established within the crust. Such bodies at high levels are regarded as delayed offshoots from the true abyssal injections, as due to discontinuous or *staccato* injection. A few illustrations may be given.

Tyrrell concluded the teschenite and picrite of the Lugar sill to have been differentiated at some deep level and then successively

thrust into the sill chamber; still later the remaining liquid at the deeper horizon was brought up and injected into the middle of the composite sill, already crystallized. At Pigeon Point, Minnesota, the dikes of red rock cutting the gabbro of the sill chamber where the red rock was differentiated are manifest examples, and many of their kind are recorded. Gilluly explains the composite sills of analcite diabase and analcite syenite of Utah (San Rafael sills) as offshoots of a somewhat older injection, a "subjacent [*sic*] laccolithic mass" which was differentiated in place, with the formation of the analcite syenite. In order to account for the garnet-wollastonite phase of a Colorado monzonite, Bastin and Hill suppose that this erupted magma remained at some deep invisible level long enough to have absorbed considerable calcareous rock.[1] Several stages of staccato injection are assumed to explain the emplacement of the composite mass represented by the Girnar laccolith of India.[2] In Mull, sediments were melted and assimilated by a basic injection before the contaminated magma was thrust still higher, to the visible levels.[3] Gevers has illustrated the principle from volcanic vents of the western Stormberg, South Africa; he considers these to be of the kind hereafter (page 393) called "subordinate," their magmas having been injected into and through the roofs of laccoliths after the laccoliths themselves had been emplaced. Shand postulates discontinuous rise of the magma at Leeuwfontein, Transvaal.[4] Specially widespread examples are furnished by the pegmatites and aplites due to "auto-intrusion."

A basaltic dike, sill, or analogous body representing magma that rose directly from the substratum, with no essential time break in the process, may be called a case of single-step or *legato* injection. This type is suspected where particularly big masses of plateau basalt, gabbro, or diabase were erupted.

It is important to recognize the distinction between the legato and staccato kinds of injection. The thermal and other conditions of a liquid at its place or places of temporary halting are different from the conditions at the higher level where this liquid, or the liquid derived from it, comes to rest. Hence the petrologist needs data beyond the

[1] G. W. Tyrrell, Quart. Jour. Geol. Soc. London, vol. 72, 1916, p. 123. J. Gilluly, Amer. Jour. Science, vol. 14, 1927, p. 208. E. S. Bastin and J. M. Hill, Econ. Geol., vol. 6, 1911, p. 465.

[2] K. K. Mathur, V. S. Dubey, and N. L. Sharma, Jour. Geol., vol. 34, 1926, p. 289.

[3] H. H. Thomas, Quart. Jour. Geol. Soc. London, vol. 78, 1922, p. 250.

[4] T. W. Gevers, Trans. Geol. Soc. South Africa, vol. 31, 1928, p. 43. S. J. Shand, *ibid.*, vol. 24, 1921, p. 248.

facts observed at visible contacts. Benson is one of those whose constructive thinking has not been discouraged by this hard necessity.[1]

The cause of the abyssal fissuring and the causes of the rise of the exotic magma are the subjects of this chapter. A brief summary of some salient facts will precede the theoretical treatment.

Abyssal Fissures

Like the cracks filled with ordinary dikes, an abyssal fissure implies breaking tension in the crust. If the substratum basalt flows out at the surface, the feeding crack is throughgoing and the whole crust has been stretched to the point of complete fracture. Many abyssal fissures have not reached all the way to the surface, probably because the rocks above their apices were not tensioned sufficiently. An example, demonstrated by prolonged mining operations, is given by the Cleveland dike of northern England.

Much of the fissuring that has permitted post-Archean eruptions is concentrated along orogenic belts. Each of these belts was the site of a major downwarp of the earth's crust or of a thick geosynclinal prism of sediments, before mountain building took place. Commonly the sediments are interbedded with flows of basalt or closely allied lava. Hence abyssal injection has been associated with mountain building, even in the preparatory stage. Some illustrations of intermittent extrusions of basalt during the growth of the geosynclinal prisms are listed in Table 31.

Table 31.—Illustrations of Volcanic Action Contemporaneous with Geosynclinal Sedimentation

1. *Lower Huronian*, North of Lake Huron (W. E. Logan, Geology of Canada, Montreal, 1863, p. 55).
   Measured section of 5500 meters of bedded rocks, with greenstone (often amygdaloidal) at seven horizons.
2. *Animikie* (*Upper Huronian*), Lake Superior District. Thick metargillites and quartzites, with interbedded extrusives at various horizons.
3. *Keweenawan*, Lake Superior District (W. C. Gordon, Mon. 52, U. S. Geol. Survey, 1911, p. 384).
   Thick sandstones, shales, and conglomerates, with extrusives at many horizons.
4. *Shuswap Terrane* (*Pre-Cambrian*), Southern British Columbia (R. A. Daly, Summary Rep. Geol. Survey Canada for 1911, p. 167).
   At least 6000 meters of limestones, altered argillites, quartzites, etc., with basic volcanics at several horizons.
5. *Grand Canyon Series* (*Pre-Cambrian*), Arizona (C. D. Walcott).

[1] W. N. Benson, Mem. Nat. Acad. Sciences, Washington, vol. 19, 1926, p. 75.

	Meters
Chuar sediments	1560
Unkar:	
Sediments	145
Lavas and sediments	245
Sediments	1665
	3615

6. *Periods of Contemporaneous Volcanism during Deposition of the Appalachian Geosynclinal:*

Period	Region
Carboniferous	Nova Scotia; Boston district
Silurian	Nova Scotia; Fox Islands, Maine
Ordovician	Cobequid Mountains, Nova Scotia
Post-Cambrian and pre-Carboniferous	Boston district

7. *Rocky Mountain Geosynclinal at the Forty-ninth Parallel* (R. A. Daly, Mem. 38, Geol. Survey Canada, 1912, p. 161). Measured section of more than 7500 meters of Beltian and Cambrian sediments, with five horizons of extrusive basalt and basic andesite.
8. *Main Pacific Geosynclinal (Compound)*, Alaska to California. Repeated extrusion of basaltic and allied magmas during prolonged sedimentation in each of the Pennsylvanian, Triassic, and Jurassic periods. In California, measured sections showing 4500 to 6000 meters of bedded rocks, including extrusives at five horizons.
9. *Cretaceous Geosynclinal in Cascade Range, Forty-ninth Parallel* (R. A. Daly, Mem. 38, Geol. Survey Canada, 1912, p. 481). About 8800 meters of sandstones, argillites, and conglomerates, overlying 425 meters of andesitic breccia.
10. *Cretaceous Geosynclinal of Vancouver Island* (G. M. Dawson). Sediments 4000 meters thick, with pyroclastics near the base.
11. *Tertiary Geosynclinal of Central Washington* (G. O. Smith).

Period	Formation	Maximum thickness, meters
Miocene	Ellensburg sediments Kecheelus andesite (extrusive) Yakima basalt Guye sediments Taneum andesite (extrusive)	 1220 610+ 1060 305

Unconformity

Eocene	Roslyn sediments Teanaway basalt Kachess rhyolite Swauk sediments	915 1220 610 1525

12. *Three British Geosynclinals.*

	Measured thickness, meters	Horizons of contemporary volcanism
A. Upper Paleozoic:		
Coal measures . .	2440	
Millstone grit . .	1675	
Carboniferous limestone series	1370	Basaltic flows
Total . . .	5485	
	Unconformity	
B. Mid-Paleozoic:		
Old Red sandstone .	3000–3650	Extrusive basalt, etc., at various horizons
Wenlock and Ludlow.	865–1060	
....	. ...	Volcanic band
Tarannon and Woolhope	350– 500	
....	.... ..	Volcanic band
Llandovery . .	425– 700	
Total.....	4640–5910	
	Unconformity	
C. Lower Paleozoic:		
Ordovician ("Lower Silurian")...	3000+	Lavas at three chief horizons
Cambrian.	3650+	Extrusive basalts and andesites at base
Total..	6650+	

13. *Witwatersrand Geosynclinal,* South Africa (F. H. Hatch and G. S. Corstorphine, The Geology of South Africa, 1905, p. 137; A. L. du Toit, Geology of South Africa, Edinburgh, 1926, p. 71).
Witwatersrand series shows 8000 meters of thickness, with surface flows at two horizons.
14. *Ventersdorp-Transvaal Geosynclinal,* South Africa.
8000+ meters thick; Ventersdorp lavas at the base, Ongeluk and other lavas of the Pretoria series, Dullstroom volcanics near the top.
15. *Geosynclinals of New South Wales* (C. A. Süssmilch, Introduction to the Geology of New South Wales, Sydney, 1911).

Age of series	Sediments	Contemporaneous	Thickness (maximum), meters
Permo-Carboniferous. ...	Sandstone, shale, conglomerate, coal	Lavas and tuffs	5400
Upper Carboniferous.	Sandstone, shale, conglomerate, limestone	Lavas and tuffs	5800

Unconformity

Devonian.............	Shale, sandstone, limestone, etc.	Lavas and tuffs at many horizons	9500
Silurian..................	Shale, sandstone, limestone, etc.	Lavas and tuffs at many horizons	3000(?)
Ordovician	Slates, shales, quartzites	Tuffs	"Thick"

During active mountain building, outflows of basalt within the limits of the deformed belt have seldom taken place on a large scale. The moderate contemporaneous eruptions, registered by "green rocks" of the Alpides and other chains, are significant exceptions to the general rule that the orogenic paroxysm is not accompanied by eruption at the earth's surface. This rule is a natural consequence of the strong horizontal compression locally affecting the more superficial rocks of the crust. However, theoretical considerations, to be later considered, suggest that extraordinary volumes of substratum basalt rise into the roots of the mountains as the deformation approaches its climax. This suggestion bears on the old problem offered by many post-Archean batholiths. The first step in the generation of each of those salic magmas seems to have been the abyssal injection of molten basalt into the Sial.

Finally, as noted below, some mountain ranges were flooded with basaltic flows after the respective batholiths themselves had crystallized.

Extensive and thick piles of plateau basalt, far removed from orogenic belts, have been mapped. Examples are the Cenozoic fissure eruptions of the North Atlantic and the Mesozoic fissure eruptions of the Deccan, South Africa, and South America. Evidently powerful and prolonged tension has caused throughgoing fissures in the crust along zones which were thousands of kilometers distant from any belt of contemporaneous folding.

Similarly, the basaltic extrusions of the deep-sea volcanoes have no direct geographical connection with known mountain structures. Reasoning from analogy with the better exposed relations of extrusive masses on the continents, we may suppose that abyssal injection of substratum material has been responsible also for the gigantic volcanoes of the ocean. These are of the central type, but their alinement, as in Hawaii, Samoa, the Society Islands, and other groups, is usually explained by assuming throughgoing fissures in the crust.

In Chapter IX two objections to the idea of an origin of basaltic eruptions in a vitreous substratum were answered. Two others are now to be met.

The first is based upon the difficulty of imagining how the basaltic material of the substratum could penetrate the overlying sheath of crystalline, but also hot, and therefore plastic, layer of crust rock. Fissuring of cool, brittle rocks is easily visualized; fissuring of the hotter, more plastic rocks at the bottom of the crust is not so readily understood. Yet all other theories of magmatic intrusion face the same difficulty. Whether now explicable or not, the eruption of every trap dike or basaltic mass proves such magmatic penetration of red-hot rock, for primary magma must in any case be topped by such a sheath. Hence we must suppose that pressure, especially by increasing viscosity, keeps the deeper crystalline rocks relatively brittle, in spite of high temperature; just as the hot rocks break at a deep seismic focus, or as a recently crystallized but hot filling of a volcanic vent is diked by a younger magma, or as a crystallized but still hot batholith is diked by pegmatitic magma.

To see that this can be true, let us consider an extreme case. Suppose that the upper edge of a vertical fissure, just entering the hot sheath, is a mathematical line, and that this fissure is filled with liquid from the substratum at pressure exceeding the pressure on the sides of the fissure. Under these circumstances, the lateral stress, tending to lengthen the fissure upward, is theoretically infinite (datum verbally supplied by P. W. Bridgman). An analogy is found in the quarryman's extension of rift fractures in granite by driving compressed air through boreholes into the rift underground. Quite moderate pressure of the air suffices to develop the fractures to considerable distances from the boreholes.[1]

It is, then, not at all incredible that the sheath of hot rock just above the vitreous substratum can become sharply fissured.

Intimately related is the second objection—that the substratum material is too viscous to occupy an abyssal fissure before wall pressure would close the fissure. This argument affects also, to some extent at least, any other explanation of primary basalt, for clearly the high pressure at any of the imagined loci of magmatic origin must raise the viscosity to high values. But the experiments of Adams and Williamson with artificial glass seem to show that the viscosity of the substratum, effective in the present problem, may be very much lower than the viscosity demonstrated for the same earth shell, when charged

[1] Verbal communication from L. LaForge. *Cf.* A. Mallock, Proc. Roy. Soc. London, vol. 82, 1909, p. 26. J. Barrell (Amer. Jour. Science, vol. 1, 1921, p. 178) was sympathetic toward the suggestion of A. C. Lane (Bull. Geol. Soc. America, vol. 5, 1894, p. 268), who, like O. Fisher, explained the diking of hot, plastic rock by the cooperation of the gas in the diking magma. In his paper Lane showed why we must believe the possibility of cracks in red-hot rock at depth.

with the much smaller stress-differences set up by body tides or earthquake waves (see page 193).

When, under horizontal tension, the crust is broken and a throughgoing fissure formed, great stress-difference is immediately created in the vitreous basalt of the substratum. With each kilometer of ascent, the glass loses both rigidity and viscosity and quickly takes on the properties of a liquid as ordinarily conceived. As the magma rises and the stress-difference at the bottom of the fissure is diminished, the pressure of the new magmatic column tends to support the walls of the fissure and at the same time to heighten the abyssal dike by continuing to exert a powerful rending effect at the top of the filled fissure.

Causes of the Ascent of Magmas

Though volcanologists have long sought the origin of what Dana called the "ascensive force" of lavas or what Spurr generalized under the name "telluric pressure," there is still no consensus of opinion on the subject.[1] Space fails for a historical review of the many suggestions, but a summary of the conditions implied by the crust-substratum system will show that some of these ideas accord with our general theory.

1. The leading cause for the ascent of primary (basaltic) magma, assumed to move up abyssal fissures, is naturally found in the weight of the adjacent crust. If the continental crust be 60 kilometers thick, the differential pressure at the foot of an abyssal fissure may at the outset be a large fraction of 17,000 atmospheres. At the same place, after the liquid has risen all the way to the earth's surface, the stress-difference is a few hundreds of atmospheres. Density relations and the observed characters of basaltic volcanoes suggest that for this reason alone basaltic liquid can rise somewhat higher than the average continental surface or above the surface of the open ocean. The potential for most of the work of eruption from the substratum is thus provided by moderate sinking (bending) of the whole crust around the abyssal fissure. An analogy is found in a reputed cause for the rise of salt domes—squeezing up the salt by the weight of the denser, surrounding rocks.[2]

The conclusions of Chapter IX imply a definite arrangement of densities in and just below the crust. The densities, like the thick-

[1] J. D. Dana, Characteristics of Volcanoes, New York, 1891, p. 170. J. E. Spurr, The Ore Magmas, New York, 1923, p. 9.

[2] See, for example, G. M. Lees, Quart. Jour. Geol. Soc. London, vol. 86, 1930, p. 521; Symposium on Salt Domes, Jour. Inst. Petroleum Techn., May and June, 1931.

nesses of the rock layers involved, cannot be stated with exactness. Though the speculative choice for the value of each quantity has a major limit and a minor limit, there still remains an infinite variety of such choices. Nevertheless, the correlation of seismological, elastic, and isostatic data can give reasonable schemes of densities and thicknesses. One such scheme is suggested in Table 32, which is intended merely to illustrate a general conception of the outer earth rather than a fixed opinion about the exact values of the quantities indicated.

TABLE 32.—EARTH SHELLS IN SECTION

		Average density of layer	Thickness of layer, km
Continent of average height:			
Crust (60 km thick)	Sial: Top, averages near granite; Middle, piezo-granite to piezo-granodiorite (?); Bottom, piezo-granodiorite to piezo-quartz-diorite (?)	2 8	40
	.... *Discontinuity*	....	.. . .
	Crystalline Sima, piezo-gabbro (amphibolitic? eclogitic?) ..	3 05	20
	. . . . *Discontinuity*	.. . ...	....
	Vitreous plateau-basalt........ .	2 82 (2 80–2.85)	20
			80
Open Pacific, deeper part:			
	(Air..................... ...	...	0 8)
	(Water	1.03	5.2)
Crust (74 km thick)	Crystalline Sima, basalt passing downward into piezo-gabbro..	3.03 –	74 0
			80
	..................*Discontinuity*	....	....
	Vitreous plateau basalt, slightly more femic than that immediately below continental crust..	2.85 (at 79.2 km below sea level)	

The mean density of liquid basalt traversing the whole continental crust with surface at normal elevation may be taken as 2.74; the corresponding figure for the oceanic section as 2.77.

Calculation will show that the pressure at the bottom of the suboceanic crust is practically equal to that at the same level under the

continent, while isostatic compensation is partly concentrated between the respective levels of the bottoms of the continental and oceanic crust blocks.[1] According to the assumed data, the top of a gas-free column of basaltic liquid, rising from the substratum and in hydrostatic equilibrium with the crust, would be about 4 kilometers above sea level in continental regions and nearly the same in the deepest part of the Pacific ocean. The difference of the thicknesses of the crust in the two regions is of the order expected on account of the contrasts of Sial and Sima in radioactivity and thermal diffusivity.

Manifestly the foregoing estimates are too uncertain to warrant more than a qualitative conclusion: the weight and flexibility of the earth's crust probably represent conditions for the eruption of lava above sea level.

2. Once risen nearly or quite to the earth's surface, a magma, even devoid of a free gas phase, must tend to rise higher because of its expansion with release of pressure. An abyssal injection with the form of a plane-parallel, vertical dike, 60 to 80 kilometers high, would bear a mean hydrostatic pressure 8500 to 12,800 atmospheres less than the same material felt before injection. The consequent expansion adds materially to the height of the magma column when in equilibrium. This is allowed for in assembling the density data of Table 32.

3. Another subsidiary cause of ascension is vesiculation of the magma. Some authorities deny any real importance for such swelling of primary basalt, but the great height of the Hawaiian Mauna Loa may in some part be explicable by the effervescence.

Morey has made it clear that the so-called "second boiling point" should be carefully considered in the present connection.[2] With the crystallization of an inclosed magma, the vapor pressure rises greatly. It seems possible that vesicles (of course, very minute) are generated in the substratum as its upper part slowly crystallizes. So, too, it may be with the peripheral crystallization of an abyssal injection itself, the liquid part thus becoming endowed with extra gas pressure (see page 368).

4. If displacements of blocks of the crust cut the connection between the magma of an abyssal injection and the substratum, so that the magma becomes sealed in the crust, continued horizontal pressure may force the liquid to higher levels. For example "tangential" pressure may have aided the eruption of the Bushveld Igneous Complex of the Transvaal, the rise of the almost incredible, magma-invaded Vredefort dome not far away, and also the emplace-

[1] Hence this speculative picture of the outer earth shells differs from those of Airy and Pratt (see page 181).

[2] G. W. Morey, Jour. Washington Acad. Sciences, vol. 12, 1922, p. 219.

ment of laccoliths in Utah and the Black Hills of South Dakota. The relation is implied for phacoliths, by definition, and may be important in the case of some lopoliths.[1]

5. Again, the collapse of geanticlines and other structures of orogenic nature is a possible condition for some basaltic eruptions.

6. Finally, the rise of certain magmas, especially the batholithic, is partly to be ascribed to stoping, that is, to a kind of convectional replacement of solid rocks of the crust by initially deeper-seated magma. That this has been a true and significant cause is argued in Chapter XII.

Abyssal Injection and the Earth's Contraction

In the year 1890 and more fully nineteen years later, Johnston-Lavis showed how abyssal injection and igneous action in general might be hypothetically explained on the basis of the classic contraction theory of mountain building. As Davison, G. H. Darwin, Reade, Fisher, Rudski, and others proved, the contraction theory implies that the superficial shell of compression is relatively thin, while beneath it is a much thicker shell charged with tension, horizontally directed. Between the two shells is a "level of no strain." Johnston-Lavis concluded that the tension in the lower shell has been intermittently relieved by the formation of vertical fissures, reaching upward to the level of no strain, these fissures being immediately filled with magma from the substratum. Continued ascent of the magma through the thin shell of compression would depend upon the local development of breaking tension in this shell, either because of unequal yielding of the heterogeneous rocks under compression or because of fluid pressure from the risen magma. Fisher had already attributed the rise of magmatic gas far up into the crust by likewise assuming fissures due to horizontal tension in the lower part of the crust.[2]

Between 1902 and 1906, the author independently imagined a similar mechanism for abyssal injection and incorporated the idea

[1] R. A. Daly, Bull. Geol. Soc. America, vol. 39, 1928, p. 761; A. L. Hall and G. A. F. Molengraaff, The Vredefort Mountain Land, Amsterdam, 1925, p. 163; L. T. Nel, The Geology of the Country around Vredefort (Mem. Geol. Survey South Africa), 1927, p. 109; regarding lopoliths, F. F. Grout, Amer. Jour. Science, vol. 46, 1918, p. 516; regarding the laccoliths, see references in Chapter VI.

[2] C. Davison, Phil. Trans. Roy. Soc. London, vol. 178A, 1887, p. 231; G. H. Darwin, *ibid.*, p. 242; C. Davison, Proc. Roy. Soc. London, vol. 55, 1894, p. 141; M. Reade, Origin of Mountain Ranges, London, 1886, p. 121; O. Fisher, Physics of the Earth's Crust, London, 2d ed., 1889, pp. 93, 279; M. P. Rudski, Phil. Mag., vol. 34, 1899, p. 299. H. Jeffreys and L. Kober are now leading advocates of the contraction theory. F. Nölke (Gerlands Beitr. z. Geophysik, vol. 38, 1933, p. 172) claims to have successfully demolished all of the published objections to this theory.

in "Igneous Rocks and Their Origin."[1] Since 1914, the objections to the classic contraction theory, while not yet sufficient to disprove it entirely, have grown weightier. Hence it cannot be used with even the former degree of confidence as the chief basis for explaining the ascent of magmas. A second reason for doubt is the apparent strength of the new theory of continental migration, with orogeny as a by-product. Notwithstanding its difficulties, this revolutionary conception will here be admitted among the possibilities, for it appears to account for many geological facts otherwise hard to understand, and particularly for some principal facts of petrology. One example is the existence of regional tensioning, fracturing, and diking of the upper part of the earth's crust at epochs that seem to be identical with epochs of strong orogenic compression in other and distant belts. The contraction theory itself demands the horizontal displacement of the crust and also its coarse brecciation along orogenic belts, so that abyssal injection and the ultimate formation of subjacent intrusions in those belts are still conceivable according to the older theory. Less manifest as a logical feature of the same theory is a cause of throughgoing fissures and diking represented on a Hebridean, Brazilian, Indian, or South African scale. On this and other grounds it seems best in the present problem to emphasize the newer theory of mountain building. Since both explanations of mountains are unproved, any deduction from either regarding abyssal injection must be loosely held and be rated as hardly more than suggestion. Yet perhaps it is worth while to ask, in the form of a detailed speculation, whether the migration theory may have the gift of prophecy and bear within it an explanation of much of the world's igneous activity, as well as of the features it was primarily designed to account for, including mountains and types of coast lines.

Abyssal Injection and Continental Migration

Mather, Snider, Fisher, Pickering, Kreichgauer, Ampferer, and Taylor had reached the conception of great horizontal displacement of continental blocks, but Wegener brought the hypothesis into general discussion. Its widespread study began only after the close of the World War.[2] Others who have either positively approved or sym-

[1] R. A. Daly, Amer. Jour. Science, vol. 22, 1906, p. 195.

[2] W. W. Mather, Geology of New York, part 1, 1843, p. 631. M. A. Snider, quoted in T. H. Pepper, The Playbook of Metals, London, 1861, p. 8. O. Fisher, Physics of the Earth's Crust, London, 2d ed., 1889, p. 339. W. H. Pickering, Jour. Geol., vol. 15, 1907, p. 23. D. Kreichgauer, Die Aequatorfrage in der Geologie, Haldenkirchen, 1902, p. 79. O. Ampferer, Jahrbuch k. und k. Reichsanstalt, Vienna, vol. 56, 1906, p. 539 (*cf.* vol. 61, 1911, p. 700; vol. 74, 1924, p. 63; vol. 76, 1926, p. 125; vol. 78, 1928, p. 347. Also Die Naturwissenschaften, 1925,

pathetically entertained the general idea are Argand, Brouwer, Bull, Cadell, Collet, Daly, du Toit, Eckardt, Evans, Groeber, Gutenberg, Heritsch, Holmes, Joleaud, Köppen, Kossmat, Lamplugh, MacCarthy, Molengraaff, Rastall, Schmidt, Schuchert, Schweydar, Schwinner, Staub, Van der Gracht, and W. B. Wright. Their opinions differ concerning the distances through which Sialic blocks have moved. Some, like Argand, du Toit, Staub, Taylor, and Wegener, assume displacements greater than 1000 kilometers. Kossmat, Schuchert, and others believe the maximum figure to be much smaller. The discussion is still lively and, whatever its outcome, can hardly fail to benefit both general geology and petrology. The bearing of the main principle of the hypothesis on the difficult problem of the origin of dry land has been noted in Chapter IX.

Some displacement of the kind has certainly affected the superficial rocks adjacent to mountain chains.[1] Just as clearly is widespread horizontal tension within the crust to be inferred from zones of normal faulting and particularly from the greatly extended coast lines of the Atlantic type. Wegener wisely insisted that the effects of horizontal tension, shown in the face of the earth, need as much attention as the effects of horizontal compression, and it is increasingly probable that the elastic behavior of the crust cannot alone account for the observed compressions. In fact, the theory of continental migration is not a little strengthened by the clear possibility of directly correlating the

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p. 669). F. B. Taylor, Bull. Geol. Soc. America, vol. 21, 1910, p. 179. A. Wegener, Geol, Rundschau, vol. 3, 1912, p. 276; Petermann's Mitt., 1912, pp. 185, 253, 305; Die Entstehung der Kontinente und Ozeane, Braunschweig, editions of 1915, 1920, 1922, and 1929 (English translation, London, 1924).

[1] L. Kober (Das Alpine Europa, Berlin, 1931, pp. 13, 279), a staunch upholder of the contraction theory, concludes that the Gondwana-Eurasia vise was closed at least 1000 kilometers and probably as much as 4000 kilometers during the Alpine orogeny. The corresponding shrinkage of the earth's crust in area is thus twenty times that found by Jeffreys for the shrinkage by cooling throughout all geological time. Kober does not adequately discuss the cause of the shrinkage, so much the greater because including that demanded, by his hypothesis, for the Altaide, Caledonide, and Pre-Cambrian revolutions. Nor does he appear to realize that crust rock is too weak to permit the storage of sufficient elastic potential required for even the Alpine displacements assumed. His latest book thus illustrates the grave difficulty faced by the contractionist who accepts ruling ideas as to the amplitudes of nappe movements in the Alpine system. H. Jeffreys (Geol. Mag., vol. 68, 1931, p. 441) appreciates the difficulty and attempts to overcome it by reviving the sliding theory of Reyer, which itself takes too little account of the strength of crystalline rock and the frictional resistance opposing the sliding of crystalline rock on crystalline rock.

However, of particular interest in the present connection is the belief of Kober, a convinced contractionist, in the extensive horizontal displacement of crust blocks of continental size.

major tensions of the crust, as "upstream" (stern) features with the "downstream" (prow) features, mountain chains and arcs. If by independent movement a continental block moved far enough to crumple a geosynclinal prism downstream, then the block must have been torn away from the Sial upstream. On the upstream side of the block the crust must have been tensioned and fractured, from top to bottom.

The hypothesis of horizontal displacements by no means excludes belief in the earth's secular contraction. In fact, distortion of the globe resulting from its contraction may have been one of the essential preliminaries to the assumed displacement of the blocks. The bodily distortion, which implies throwing the crust out of level, gives the higher parts of the warped crust gravitational potential and thus might be conceived to supply some of the required energy, if Sialic blocks moved at all. The elastic potential, supposed on the classic contraction theory of mountains to have been stored in the shell of compression, would be largely lost if great blocks of the crust thus slid independently over the earth's body. But, during the long periods intervening between epochs of continental sliding and corresponding orogeny, the crust would be intact, and progressive contraction would theoretically lead to the generation of shells of compression and tension. Both kinds of stress might be feebler than those expected, in maximum, on the classic theory. Yet, however weak, the tensions in the lower shell would tend to facilitate abyssal injection after the fashion described in "Igneous Rocks and Their Origin." The mechanism there outlined, as a speculative deduction from the classic contraction theory, is not here discussed, for two reasons: first, to save space; second, because the migration theory, in spite of its need of more support, appears to offer a reasonable alternative suggestion about a leading phase of petrogenesis. The assumption that blocks of continental dimensions have moved horizontally and independently, at least moderate distances, prompts the question of present interest: Can abyssal injection, the ascent of magma into and through the crust, be largely attributed to crustal tensions produced when blocks of the Sial migrated?

Before considering the subject, an incidental point may be made. According to the classic contraction theory itself, broad tracts of the Sial were displaced horizontally, whenever, during the orogenic act, the shell of compression was sheared away from, and sheared horizontally over, the shell of tension. Recumbent folds, nappes, and the arcuate form of mountain chains prove notable horizontal movement of extensive areas of a superficial layer of the crust. The classic theory holds that these displacements took place by the horizontal scission

of the crystalline crust over much or all of the earth. In view of even the moderate strength assignable to the crust at the level concerned, the possibility of such scission by the available force is at least open to question. Very different is the situation if the scission be supposed to have taken place within an indefinitely weak, because vitreous, substratum.

The theories involving horizontal displacement of blocks with the full thickness of the crust may be divided into two groups, according as their authors assume the blocks to have been forced to their new positions because of (1) frictional pull at the bottom of each block or (2) a direct gravitational pull.

By hypotheses of the first kind, subcrustal, horizontally directed currents have dragged crust blocks of continental size with force sufficient to crumple rocks on the fronts ("prows" or "downstream sides") of those blocks. Thus the mountain structures were formed, drag folds and drag thrusts predominating.

Such a suggestion was early made by Fisher, who assumed the dragging undercurrent to be of convectional origin. The same general idea appears in the orogenic theories of Ampferer, Schwinner, Groeber, Bull, Holmes, and Kirsch. Wegener himself in the 1929 edition of his book (page 184) approved the Bull-Holmes-Kirsch version of the hypothesis as supplying an important cause for the migration of continents.[1]

The explanation of mountain chains by the direct drag of thermal-convection currents is subject to doubt. In the first place, can the assumed horizontal current exert enough viscous pull on a continental block so that the rocks on the "prow" side shall be crumpled and thrust? All mountain building appears to have been an exceedingly slow process in absolute measure. During one of these prolonged periods one would expect the elastic coupling between crust and substratum to be completely broken by viscous displacements in the

[1] O. Fisher, Physics of the Earth's Crust, London, 2d ed., 1889, p. 318. O. Ampferer, Jahrbuch k. und k. Reichsanstalt, Vienna, 1906, p. 539, and 1911, p. 700; Die Naturwissenschaften, 1924, p. 1007, and 1925, p. 669. R. Schwinner, Zeit. f. Vulkanologie, vol. 5, 1920, p. 203. P. Groeber, Bol. Acad. Nacional de Ciencias en Cordoba, Buenos Ayres, vol. 30, 1927, p. 177. A. J. Bull, Geol. Mag., vol. 58, 1921, p. 364, and vol. 68, 1931, p. 495; Proc. Geol. Assoc., vol. 38, 1927, p. 155, and vol. 40, 1929, p. 105. A. Holmes, Geol. Mag., vol. 65, 1928, p. 236; Mining Mag., April–June, 1929, sep. p. 1; Trans. Geol. Soc. Glasgow, vol. 18, 1929, p. 559.

Whatever strictures may be applied to it, the undercurrent hypothesis claims attention because, more simply than other hypotheses, it might seem to solve certain major problems: the cause of the amazingly serpentine course of the Alpine system in its ground plan; the intensity of the deformation in the Patagonian Cordillera, the East Indies, and similar regions of areally restricted Sial; and such features as the Falkland Island and Windward Island arcs.

substratum. Unless, then, the material of this shell did retain some undecayed rigidity or what amounts to strength, it could not force the crust to do the great work of orogeny. Yet thermal convection is impossible in a medium that has finite strength.

Again, it is hard to conceive of currents moving horizontally under the crust through the required distances of thousands of kilometers, if the convectively stirred earth shell is thin. Yet we have seen that any thermal convection in the earth on the large scale has probably been of the "tandem" kind, and we cannot with safety accept single-step convection in any shell more than a few hundreds of kilometers thick. If with Holmes we assume convection in a shell bottomed by the 2900-kilometer discontinuity, and rise of the deep material all or nearly all of the way to the crust, we encounter another setback. For the temperature at the depth of 2900 kilometers is probably not much lower than half of the 10,000° calculated by Holmes. The expansion of this exceedingly hot material in the rising branch of the current should be enough to lift the crust in that sector 10 or more kilometers, and the ultimate temperature near the surface would much exceed that of mere fusion of the crust. Neither consequence matches the geological record. Nor is there any evidence that the opposite tendencies in the sector occupied by the diving branch of the postulated current have left their mark on the globe.

Thus the objections to the idea of dragging of the crust by convection currents as a major cause of orogeny seem strong. On the other hand, perhaps thermal convection has *indirectly* prepared the conditions for mountain building—specifically by moderate deleveling of the crust, which then *slides* on the weak substratum.

It is worth noting that a complete discussion of terrestrial convection would cover not only that due to radiation from all parts of the surface but also the contrasted rates of radioactive heating in different sectors. Would one also need to consider Darwin's idea that tidal heating when the planet was young developed a higher internal temperature under the polar caps than under the equatorial belt?[1]

Another type of subcrustal current was visualized by Hayford and later by Lawson and then DeLury: mountain structures are the effects of the drag exerted on the upper rocks of the crust by deep currents set up during isostatic adjustments.[2] The adequacy of this process has not been demonstrated.

[1] A. Holmes, Trans. Geol. Soc. Glasgow, vol. 18, 1929, p. 559. G. H. Darwin, Scientific Papers, Cambridge, vol. 2, 1908, pp. 160, 163. See also footnote on p. 220.

[2] J. F. Hayford, Science, vol. 33, 1911, p. 199, and Proc. Washington Acad. Science, vol. 8, 1906, p. 38. A. C. Lawson, Bull. Geol. Soc. America, vol. 33, 1922, p. 337. J. S. DeLury, Trans. Roy. Soc. Canada, vol. 25, *iv*, 1931, p. 199, with reference.

Kreichgauer was one of the first to propose a hypothesis belonging to the second group. He pointed out that a high-standing block of the crust, situated at some distance from the equator, tends to slide toward the equator; the tendency is due to the rotation of the earth. Kreichgauer supposed the pressure on the equatorward side of the moving block to be the general cause of mountain building, a view which logically led him to assume also important shifts of the earth's axis of rotation, relatively to the crust. Lambert and Epstein have estimated the maximum possible amount of such pressure. It was found to be exceedingly small. Nevertheless, Wegener believed it to be one of the chief causes of continental migration.[1]

Taylor assumes crustal sliding and consequent orogenic pressure, directed equatorward and caused by increase of the oblateness of the earth during Cenozoic time. His hypothesis gives no explanation of the Hercynian (Variscian) chain, developed long before the Cenozoic.

Wegener sought one cause of continental migration in the westward pull on the Sial, exerted by precessional forces. Schweydar's computation of these forces shows that the downstream pressures are, here also, extremely small and doubtless of negligible importance in orogeny.[2]

Joly makes the tide-generating forces responsible for westward displacement of the whole crust of the earth, but, unlike Wegener, he ignores the differential pull on the Sial and thus assumes no significant overriding of the suboceanic Sima by the Sial, with the implied tensioning of the crust. As noted in Chapter IX, Joly explains abyssal fissuring—legato injection—by periodic expansion of the substratum.

Full discussion of these different explanations of mountains cannot here be undertaken, but some essential facts and apparently necessary postulates may be stated.

First, cosmical force sufficient for the displacement of Sialic blocks, continental in size, has not yet been discovered. No force other than gravity seems worthy of consideration. Thus, if continental blocks have moved horizontally more than a few kilometers, they either slid or were dragged, and the energy was provided by the earth's own gravitational potential. An acceptable theory of continental migration is not likely to be a "drift" theory.

Second, the displacement demands the *pari passu* foundering of crust blocks on the downstream (prow) side of each moving continent.

[1] D. Kreichgauer, Die Aequatorfrage in der Geologie, Haldenkirchen, ed. 1, 1902, p. 71; ed. 2, 1926, p. 55. W. D. Lambert, Amer. Jour. Science, vol. 2, 1921, p. 132. P. S. Epstein, Die Naturwissenschaften, vol. 9, 1921, p. 499. A. Wegener, The Origin of Continents and Oceans, London, 1924, p. 199.

[2] W. Schweydar, Zeit. deut. Gesell. Erdkunde, Berlin, 1921, p. 120.

The suboceanic crust, like the Sialic, is strong—strong enough to bear the positive load of a giant Hawaiian volcano and the negative load of a Tonga Deep. Wegener's postulate of essential liquidity for the Simatic crust is quite without warrant. On the other hand, foundering of pieces of the crust is impossible if density in the earth increases steadily downward from the surface. Foundering *is* possible on the theory presented in this book. It seems not too much to say that the possibility of continental migration depends upon the existence of a vitreous substratum—basaltic since an early Archean epoch, possibly more salic during a preceding period of the earth's history.[1]

Accordingly, because the crust-substratum theory has some independent merit, the author has long believed it to be good scientific practice to retain the migration hypothesis as one of the working tools. Its early examination soon showed the weakness of the "drift" form of the hypothesis. In its place a "downsliding," "landslide," or "crust-sliding" version has been published in outline.[2]

Before each displacement, the continental crust is assumed to have been out of level and not merely "floating" and standing level in the Sima, as Wegener thought. Under the horizontal tension produced

[1] Nearly all presentations of the hypothesis of continental migration fail to account for the fate of the overridden part of the continental crust. According to Argand, Collet, Heim, Kober, Staub, and Termier, Eurasia and Gondwanaland were forced together, when the Alps were formed, through a distance of at least twice the width of the Swiss Alps. Hence in the belt of overriding, the Sial must have been doubled, or more than doubled, in thickness. Yet in most of the illustrative sections published by the authors named, the thickness of the Sial along the mountain belt is shown as little different from that normal elsewhere. For instance see E. Argand (La Tectonique de l'Asie, Liége, 1924, Figs. 16 to 19) and R. Staub (Der Bau der Alpen, Berne, 1924, Tafel 8). The difficulty is felt the more keenly because both of these writers hold the Sial to be under all circumstances less dense than the Sima and thus incapable of foundering in it. Both writers represent a pronounced thinning of the Sial at the edges of the overriding and overridden parts of the crust, but give no reason for the acute-wedge forms. In general, it seems impossible to conceive of the mechanical conditions which would permit such displacements as those portrayed in the sections. But explanation of the Alpine nappes appears eminently possible on the assumption that foundering of large blocks of the crust took place within the orogenic belt. If the blocks were melted in the Sima, their material would necessarily spread beyond the belt to some distance. Thus the final isostatic adjustment would not give the mountain chain an average height so great as that expected on the hypotheses of Argand and Staub. On either hypothesis it is not easy to understand the moderate average height of the Alps, if they were formed by a shortening of the earth's crust by more than 200 kilometers.

L. Kober (Das Alpine Europa, Berlin, 1931, pp. 52, 66) has also observed the error of principle involved in the sections drafted by Argand and Staub.

[2] R. A. Daly, Amer. Jour. Science, vol. 5, 1923, p. 365; Proc. Amer. Phil. Soc., vol. 64, 1925, p. 283; Our Mobile Earth, New York, 1926, p. 260.

by the deleveling, the crust is supposed to have been broken into large blocks, one or more of which slid down along the interface with the weak substratum. Gravity supplied the potential for overcoming the friction beneath each block and also for mountain building on the downstream side of the block. Each block may be likened to a giant landslide, derived by the break-up of an extensive dome or arch of a distorted planet. An analogy is illustrated in Fig. 94, where the chilled and already plastic-solid skin of a lava flow slid on the viscous-liquid or weak-solid interior of the flow, powerfully striating this glassy

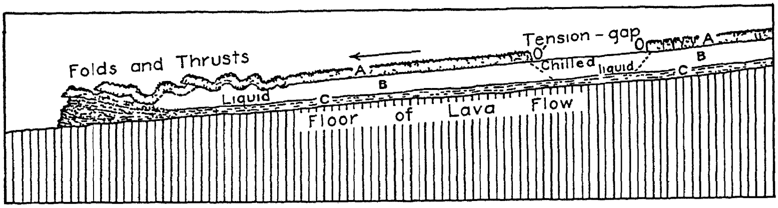

Fig. 94.—Diagrammatic section of a basaltic flow in Ascension Island, illustrating the sliding of a chilled, plastic-solid layer A on viscous-liquid layer B, with resulting folds and thrusts downstream and tension gap upstream As B was bared, it rapidly attained rigidity and strength (See Proc. Amer. Acad. Arts and Sciences, vol. 60, 1925, p. 19.)

material as the sliding progressed.[1] The folded and thrust "skin" downstream corresponds to the mountain structure assumed to be caused by such slipping of the continental block on the hot vitreous substratum. The analogy of ordinary landslides with orogeny was pointed out by Reyer, Schardt, Reade, and A. Penck, and has recently been emphasized by von Post with examples from Sweden. We have observed that Jeffreys has revived the idea to explain nappes. In some respects the gliding hypothesis of Haarmann, involving geotumors and geodepressions, is like that of the present writer.[2]

How the earth came to be distorted, with widespread deleveling of the continental part of the crust, is a complex problem. Lack of space forbids a proper analysis, but possible conditions for the distortion may be listed:

1. Secular contraction of the earth.
2. Regional erosion and regional loading of the crust with sediments and ocean water.

[1] H. T. Stearns (Water-supply Paper 616, U. S. Geol. Survey, 1930, p. 121) has recently described what appears to be a case parallel to the Ascension Island sliding of solid lava on viscous lava.

[2] A. Penck, Zeit. Gesell. f. Erdkunde, Berlin, 1908, p. 5. L. von Post, Geol. Fören. Förh. Stockholm, vol. 49, 1928, p. 503, and vol. 50, 1929, p. 756. H. Jeffreys, Geol. Mag., vol. 68, 1931, p. 435. E. Haarmann, Die Oszillationstheorie, Stuttgart, 1930.

3. Decrease of the earth's velocity of rotation.
4. Differential radioactivity and associated differential cooling and contraction of earth sectors.
5. Convection in the substratum and still deeper in the earth's body.

The differential effects suggested in items 2, 3, and 4 are deduced from the steady existence of land and water hemispheres, Sialic crust, and Simatic crust throughout geological time; and the persistence of shields and major geodepressions (including the "mid-latitude furrows") within the land hemisphere. Presumably the shield areas stood higher than the geodepressions, because the Sial was thicker in the shield sectors, and the thicker the Sial the greater was the radiothermal action. If the heat of radioactivity correspondingly retarded the secular thickening of the crust, this differential effect would increase the height of the shield relatively to the adjacent geodepressions; relatively higher would become dome or arch. In an analogous way the crust of the land hemisphere could not fall, with the contraction of the earth, so fast as the crust under the primitive ocean. Hence there was also a tendency for the development of a sliding slope oceanward (toward the Pacific).

Continued contraction led to the deepening of the geodepressions with their local geosynclines. These depressed belts were held down partly by the strength of the crust. It is conceivable that such warpings of the crust, though of small amplitude, sufficed to direct convection in the interior, the corresponding domed or arched sectors becoming somewhat hotter and more expanded than those under the geodepressions. If the more radioactive, hotter, and less dense parts of the substratum tended slowly to rise, they might collect under dome or arch and there cause further expansion of these sectors. Thus the crust might become thinnest, as well as highest, at dome or arch. In its new deleveled state, the crust is still isostatically supported but is now in danger of sliding, if it is broken at a geodepression where the thicker, denser part of the crust has been bent down into, and threatens to founder in, the substratum.

The formation of the shields and correlated mid-latitude furrows, whose existence in pre-Cretaceous time is shown by the paleogeographic maps, is a problem about as baffling as that of the segregation of the Sial as a whole. Can we hope to find a clue in the change of the earth's angular velocity, which, by theory, was specially rapid in pre-geological and early geological time?[1]

That any one of the listed conditions or any combination of them has actually given potential adequate for continental sliding remains an open question. Yet we should continue to ask it, for even slight

[1] R. A. Daly, Amer. Jour. Science, vol. 5, 1923, p. 372.

deleveling of a crust resting upon a substratum of practically zero strength could not fail to furnish much more power than that derived from any known force (apart from that due to contraction) acting upon the crust in a state of pure flotation. Moreover, in this problem we must never lose sight of the principle of the concentration of stress when an elastic structure collapses. While the mean pressure on the downstream side of a moving block was not great in absolute measure, the inevitable concentration of pressure at successive points may well have sufficed for folding and thrusting of rocks downstream.

Finally, it is natural to imagine the cooperation of both sliding and drag in the horizontal displacement of continents. Convection currents themselves progress by a kind of sliding.

Elusive as the cause or causes may be, we can no longer deny at least moderate regional displacements of the Sial in latitude or longitude or both. The earth's general plan, the mountain arcs and foredeeps, the transverse shortening of geosynclinal prisms, and other facts of observation seem to prove that the Sial, either by its own expansion or by the freeing of large, independent blocks, moved toward a mid-latitude "furrow" in each of the two—northern and southern—hemispheres; and also that at least large fractions of the Old World continents moved eastward, toward the central Pacific region, large fractions of the two Americas moving westward.[1]

Assuming some migration of continental blocks, let us try to trace its consequences for petrological theory. To avoid the wearisome use of verbs in the conditional mood, the processes associated with the displacement will be described as actually under way. Inasmuch as the whole analysis is understood to be speculative, the reader will not be misled by this more direct method of expression.

On the "upstream" side of the moving continent the earth's crust has been under tension, a condition changed by vertical fracturing (abyssal fissuring) when migration begins. The fissure is immediately filled with basaltic magma, risen from the substratum. The liquid may flow out at the surface, but that quickly frozen in the dikelike fracture represents a new, narrow element of the earth's crust. Further migration leads to a succession of such fracturings and dike extensions of the new crust, probably capped with floods of basaltic lava. Thus, since the migration is necessarily slow, the wounded original crust upstream is healed with Simatic material.

Its relatively high density causes the new crust at the scar to stand low, and, if the horizontal movement is great enough, the new crust

[1] See R. A. Daly, Our Mobile Earth, New York, 1926, p. 278. Much the same belief regarding the directions of displacement is held by A. Holmes (Nature, vol. 122, 1928, p. 433; Trans. Geol. Soc. Glasgow, vol. 18, 1929, p. 588).

becomes covered with a deep ocean. Henceforth this Simatic part of the crust is invisible. However, the tensioned edge of the moving continent itself is also liable to diking and flooding by lava, and the mechanism can there be studied. An example seems to be represented by the dike swarm and associated plateau basalts of the Island of Mull, where a 20-kilometer belt of the Sial has been widened during the injection of basaltic dikes (432 in number), totaling 825 meters in width. The adjacent region of Arran has been similarly stretched, widened from 23 kilometers to 24.7 kilometers, with the injection of 525 dikes (see Fig. 20). A third illustration is found in the volcanic belt of Lebombo, South Africa, where du Toit describes a swarm of north-south doleritic dikes, indicating crustal tension in an east-west direction.[1]

The traps extruded over an immense region, stretching from Franz Josef Land into Siberia, are contemporaneous with the long-continued deformations of the Tethyan zone, far to the south. The basalts of Greenland, Iceland, and the North Atlantic in general are contemporaneous with the Alpine compression—a long process. Perhaps the basalts of the Newark system were poured out because eastern North America was under the tension which, a little later, was to become stronger during the Jurassic revolution of the Pacific coast. Nearly contemporaneous with the Newark lavas are the basaltic floods of Brazil, Uruguay, and South Africa. The countless dikes associated with these flows seem to show that the Atlantic region as a whole was being slowly stretched.[2]

More complicated are the igneous processes on the downstream side of the migrating continent. There a geosynclinal prism of sediments has long been thickening and so weakening the crust. In this zone of sedimentation the crust is sheared, fractured throughout its whole thickness. Lateral support for the domed, or arched, deleveled Sial is thus locally withdrawn, and, as we have just seen, somewhere in its central region the dome or arch is tensioned and finally broken, with the formation of two or more large "continental" blocks. Migration of one of the blocks begins, directed toward the geosynclinal.

The plane of major shearing under the sedimentary prism is an inclined abyssal fissure, along which basaltic liquid from the substratum is injected. One effect is to "lubricate" the shear plane, whereby the resistance to further migration of the continental block is lessened. Another essential effect is the development of a downward pull on the underthrust rocks belonging to the lower part of the crust.

[1] E. B. Bailey and G. V. Wilson, Mull memoir, Geol. Survey Scotland, 1924, p. 360. G. W. Tyrrell, Arran memoir, *ibid.*, 1928, p. 248. A. L. du Toit, Trans. Roy. Soc. South Africa, vol. 18, 1929, p. 216.

[2] R. A. Daly, Proc. Amer. Phil. Soc., vol. 64, 1925, p. 298.

For these rocks are slightly more dense than the vitreous Sima and, if immersed in it partly or wholly, tend to sink in it. With complete immersion sinking is inevitable. The process may be called *major stoping*. The thick layer of the crust below the lighter geosynclinal rocks is bent down; the abyssal fissure accordingly widens. A bottomless mass of molten Sima rises into the crust, reaching up to the crumpled rocks of the unsinkable geosynclinal prism (see the accompanying Fig. 95 and compare Figs. 166 and 168 in the author's "Our Mobile Earth").

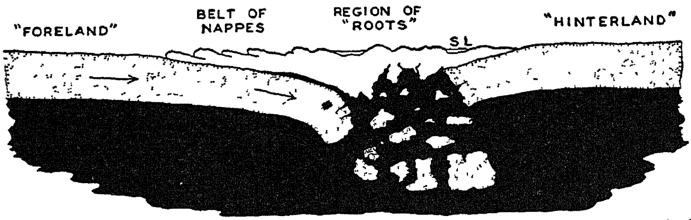

Fig. 95.—Diagrammatic section to illustrate underthrusting of the crust (*stippled*), development of nappes from geosynclinal sediments (*blank*), and major stoping in the vitreous substratum (*solid black*).

The moving "continent" is now fronted by the great molten injection underlying the comparatively weak rocks of the geosynclinal prism and probably some of the stronger Sialic rock beneath the prism. Since the initial elastic resistance of the crust has been thus lowered, the migration is accelerated. The horizontal pressure of the moving continent is largely concentrated upon the weak prism (in vertical section). Moreover, the pressure is still further concentrated at the specially weak places along the axis of the geosyncline (in ground plan). In succession, point after point feels the maximum pressure, which may run into thousands of atmospheres. Because of such concentration, the pressure seems adequate to produce the complex folds, thrusts, and rafting-together of the typical mountain chain.

The crumpling continues until the dwindling gravitational potential becomes too small to break down the elastic and frictional resistance to continued migration, or until the crowding of the substratum with fragments of the crust forbids further stoping on the big scale. Except for minor features, like normal faults and late volcanism, the mountain structure is now complete.

According to this speculative picture of the general process, the eruptive mechanism at the downstream side of the continent will be briefly outlined.

The geosynclinal prism has been folded and sliced (nappes) in either of two ways: (*a*) by direct end-on pressure against the prism by the moving continent, assumed to *override* the old Sialic rocks below

the prism, or (*b*) by frictional drag of the moving continent as its edge *dives* at a low angle *under* the geosynclinal belt (drag folds and drag thrusts). Although the first possibility is more commonly preferred in explanation of actual mountain structures, the alternative hypothesis, particularly when applied to the Alps, seems to involve fewer mechanical difficulties. In fact, Ampferer prefers to think of Europe as underthrust, the absolute motion responsible for the Alps being toward the south, and doubtless welcomes the experimental results of MacCarthy and Bull, both of whom appreciate the great importance of subcrustal plasticity in the orogenic problem.[1]

The hypotheses of overthrusting and underthrusting involve magmatic effects that are in part essentially similar.

1. From the basaltic mass, injected at the primary fracture under the geosynclinal prism, surface flows of basalt may occasionally appear during the orogenic crumpling, in spite of the existence of general horizontal compression in the belt. Some of these eruptives will pass down into the other bodies of "green rocks," which have been intruded along the "soles" or listric interfaces of the terranes sliced by the continental pressure.[2] Continued folding and thrusting metamorphose such early eruptives.

2. The downflexed part of the crust and the huge fragments of the crust that founder at the downstream edge of the moving continent are *pulled* down, under the influence of differential density, to levels of high temperature. At those levels the depressed and sunken rocks are melted and partly dissolved in the hot substratum.[3] Whether melted or dissolved, these masses, because somewhat more felsic than basalt, give magmas which are less dense than the substratum. Hence the secondary magmas, so formed on a large scale, rise and invade the roots of the new mountain chain above. There the density relations favor magmatic stoping. In contrast with such major stoping, the more ordinary, piecemeal stoping will replace relatively small volumes of the solid crust with magma. Nevertheless, the magmas by ordinary stoping may rise some hundreds, or a few thousands, of meters into the mountain roots before the magmas freeze solid.

[1] G. R. MacCarthy, Amer. Jour. Science, vol. 16, 1928, p. 51. A. J. Bull, Proc. Geol. Assoc., vol. 40, 1929, p. 105.

[2] See E. Suess, La face de la terre (translation by E. de Margerie), Paris, vol. 3, 1918, p. 1497; E. Argand, La tectonique de l'Asie, Compte Rendu, 13th Cong. Géol. Internat., Liége, 1924, pp. 348–353.

[3] According to L. Kober (Das Alpine Europa, Berlin, 1931, pp. 52, 66) Sialic rocks that are depressed during the formation of a mountain chain are melted, and this secondary magma is resurgent into the roots of the chain. His deduction seems reasonable if, as he assumes, major orogeny is conditioned by the extensive horizontal displacement of the crust toward the orogenic belt.

The final results are bottomless intrusive masses with their satellitic dikes, sills, laccoliths, chonoliths, and surface volcanics. In general, the invading masses will be of granitic, granodioritic, dioritic, rhyolitic, dacitic, or andesitic nature, according to the march of assimilation and differentiation as well as of preliminary pure melting of Sialic material in the substratum.

3. The cooling of the intrusive masses and of the mountain rocks, which had been heated in the stress of orogeny, causes contraction and breaking tensions in the *upper* part of the mountain structure. Other horizontal tensions may be expected at high levels in the crust, if, as seems generally to be the case, the new structure as a whole is arched or domed up long after the folding and in consequence of expansion of the rocks which had been sunk to great depth and there slowly heated. If the horizontal tensions reached sufficient magnitude, the mountain structure and in fact the whole crust are fissured. Fresh tapping of the substratum, with abyssal injection and surface flooding with basaltic lava, are the expected results. Herein we have plausible explanation of the post-orogenic eruptions of plateau basalt, listed in Table 33.

TABLE 33.—RELATION OF FISSURE ERUPTION TO MOUNTAIN-BUILDING PERIODS

Locality	Date of fissure eruption	Preceding orogenic period
Lake Superior District	Keweenawan	Close of the Animikie
Rocky Mts at 49th parallel	Middle Cambrian (?)	Early Middle Cambrian (?)
British Islands	Devonian	Caledonian
British Islands	Carboniferous	Hercynian
Appalachian Mountains	Triassic	Close of Paleozoic
British Columbia	Triassic	Carboniferous
Deccan, India	Cretaceous (or early Tertiary?)	Late Triassic (also later?)
Great Rift, Africa	Cretaceous (Kaptian series)	Late Triassic (also later ?)
State of Washington	Eocene (Teanaway basalt)	Close of Laramie
Northwestern Scotland	Oligocene (Lower Miocene)	?
Iceland	Miocene	?
State of Washington.	Miocene (Yakima basalt)	Post-Eocene and pre-Miocene
Great Rift, Africa	Miocene (?)	Tertiary (Alps, etc.)
Great Basin, U S.A.	Pliocene	Miocene
Snake River, Idaho	Pliocene	Late Miocene
Hauran, Syria	Pliocene	Earlier Tertiary
Iceland	Pleistocene and Recent	Tertiary

In conclusion, it appears that igneous activity, directly or indirectly associated with mountain building, finds reasonable explanation on the theory of continental migration, even if quite limited in distance of travel. That theory itself is based on fundamental assumptions regarding the nature of the earth's outer shells. For manifest reasons, therefore, the described matching of deductions and actual observations is suggestive rather than demonstrative of the writer's theory. The problem is new and immensely complicated, and final judgment as to the mechanism of eruptions preceding, accompanying, and following orogeny must be reserved for the distant future. The writer has

tried to present his own best guess about the relations in space and time. Less subjective is the logical inference from any and all of the rival explanations of the displacements of independent blocks of the Sial. We have seen that opinions vary as to the maximum amount of migration of blocks, but, irrespective of the range of movement, breaking tension in the crust and the possibility of abyssal injection of magma are implied by each of these opinions. Comparatively little displacement of crust blocks would account for much of the post-Archean fissuring of the crust and igneous eruption. Hence the petrologist who accepts the idea of continental migration is not under the immediate necessity of assuming displacement of crust blocks to the extent of many hundreds of kilometers. In any case the student of the mechanics of magmatic eruption can no longer ignore this new orogenic theory. If, however, future research should give greater weight to the contraction theory, this also should be considered with reference to the idea of a thin crust and the correlated distribution of densities and of strength in the outer earth shells. Both theories involve the horizontal displacement of crust rock *toward* the geosynclinal belt, and this is now seen to imply vertical, downward displacement of crust rock *in* the belt. Such subsidence must be by downthrusting or downpulling, with the development of deep mountain roots, or by foundering of large pieces of the crust, or by both processes. If the material beneath the crust were crystalline and denser than the crust, neither downthrusting nor foundering on the required scale would be possible. Both are possible on the assumptions of the general theory of this book.

Other Conditions for Abyssal Injection

Probably basaltic eruption has been produced through causes which have had no immediate connection with the horizontal displacement of separate blocks of the crust. The nature of those causes is obscure, particularly those responsible for the growth of the deep-sea volcanic cones. As above noted, the alinement of the oceanic volcanoes strongly suggests abyssal fissuring on a large scale, but the throughgoing cracks in the crust seem here not to be readily explained by the migration of distant Sialic blocks; nor are they obviously related to the stresses set up by the earth's contraction. The general northwest-southeast alinement of the volcanic islands in the open Pacific has indicated to some authorities the probability that the earth as a whole has undergone torsion sufficiently strong to open the erupting fissures; but convincing tests of this hypothesis have not yet been invented.

SUMMARY

Fissuring of the Sial is a corollary from visible diking by basaltic material. That many dikes are abyssal, bottomless, is an assumption without possible absolute proof. On that basis, however, we can understand the facts suggesting staccato as well as legato injection. Abyssal fissuring and consequent basaltic eruption appear to be connected with the development of geosynclines and also with orogenic belts. Six different conditions for the rise of magma along or from abyssal fissures have been discussed. Most of the fissuring itself is speculatively attributed to at least moderate horizontal movement of Sialic blocks of continental or subcontinental dimensions. Much of the actual breaking and injection of the earth's crust, particularly that far distant from the mountain chains, is not so readily explicable on the classic contraction theory, which, nevertheless, should also be retained among the working hypotheses of mountain building and igneous action. The presumed fissuring of the sub-Pacific crust, indicated by a score of major volcanic chains, seems to be a separate problem.

CHAPTER XII

MAGMATIC STOPING

INTRODUCTION

Mount Ascutney, Vermont, is essentially composed of three large intrusions, two of which are typical stocks. The three were emplaced in the order of increasing acidity (Fig. 96). For nine years the writer

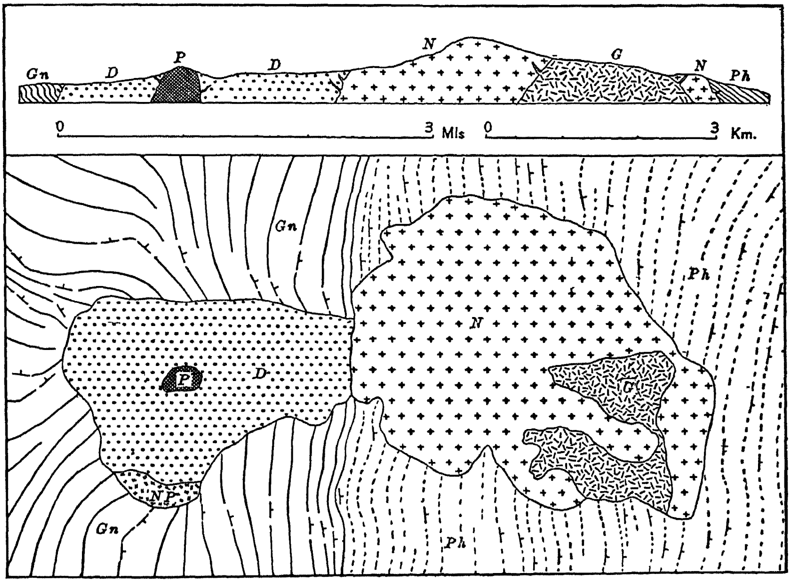

FIG. 96.—Map and section of Ascutney Mountain, Vermont, showing replacement of phyllites and gneisses by a composite stock. *G*, granite stock; *N*, nordmarkite stock; *NP*, nordmarkite porphyry and paisanite; *P*, pulaskite; *D*, diorite stock with gabbroid and essexitic phases; *Ph*, phyllites with thin limestone interbeds; *Gn*, gneisses with thick limestone pods interbedded. Symbol for strike and dip. (*From Bull.* 209, *U. S. Geol., Survey*, 1903.)

was baffled in the attempt to explain their mode of intrusion. Ultimately a reasonable hypothesis became disentangled from the mass of facts compiled from this local study and from the relevant literature of experimental physics. The principle involved was given the name *magmatic stoping*.[1]

[1] See Bull. 209, U.S. Geol. Survey, 1903, p. 93. Also Amer. Jour. Science, vol. 15, 1903, p. 269; vol. 16, 1903, p. 107; vol. 26, 1908, p. 17.

It was then found that the central idea had already impressed itself on Lawson as well as Goodchild, although neither of these geologists elaborated the subject. Again independently, Barrell had deduced a similar mechanism for the stock at Marysville, Montana, and in 1907, after several years of delay, was allowed by the authorities of the United States Geological Survey to publish his "revolutionary" conception. Still later (1911) the great work of Ussing on the Julianehaab region, Greenland, was issued, bearing the information that its author had invented the stoping hypothesis during the year 1900.[1]

Types of Stoping

For each of the geologists listed, the conception resulted directly from the pressure of field facts. Each saw the problem as relating to the *completion* of the magmatic emplacement—to the last stage of the magma's upward invasion of the earth's crust. The various statements of the hypothesis did not equally emphasize the role of differential density in compelling the subsidence of xenoliths. This principle seems vital, and here the term "stoping" will mean subsidence or ascent of included blocks because these have densities contrasted with that of the inclosing melt. In the usual case the xenolith is the denser and sinks. By continued fracturing of wall or roof, continued immersion of corresponding fragments, and continued subsidence of these fragments, the magmatic chamber is enlarged upward or sideways or in both senses. Such replacement of country rock accounts to a certain extent for the intrusion. The vertical thickness of the replaced rock for various bodies may not unreasonably be stated in terms of tens, hundreds, or possibly a few thousands of meters. For convenience this type of magmatic replacement, the dislodgment of comparatively small pieces of crust rock, either singly or in one or more "showers," may be called *piecemeal stoping.*

Piecemeal stoping on different scales has been described by scores of field men, but few have discussed the relation of the process to petrogenesis. The difficulty of discerning that relation partly explains their reticence. On the other hand, a few authorities, including H. Cloos, Harker, Iddings, Kayser, Kemp, and Lindgren, have decided that stoping is practically negligible in the problem of magmatic origins. None of these six writers has justified his conclusion by good evidence.

[1] A. C. Lawson, Science, vol. 3, 1896, p. 637. J. G. Goodchild, Geol. Mag., vol. 9, 1892, p. 447, and vol. 1, 1894, p. 22. J. Barrell, Prof. Paper 57, U.S. Geol. Survey, 1907, pp. 151–174.

W. Salomon (Geol. Rundschau, vol. 1910, p. 13) saw the necessity of explaining some of the upward advance of the magma of the Adamello ethmolith by stoping.

This chapter will consider not only the piecemeal stoping of the original hypothesis but also two additional kinds, one of which may yet be recognized as, for petrogenesis, the most important of all.

Does the "cauldron-subsidence" kind of injection, which, according to the Scottish geologists, emplaced the Glencoe, Ben Nevis, and Etive granites, fairly suggest a kind of stoping hitherto not familiar in geological theory? The same question arises in connection with the Slaufrudal granophyre stock of Iceland, if "the replaced mass of country-rock sank 'en bloc' rather by piecemeal stoping"?[1] Richey attributes the intrusion of the Irish Mourne granites to the sinking of a large block of the crust, but does not mention contrast of density as a possible cause of the subsidence. Figure 97 illustrates his conception.[2]

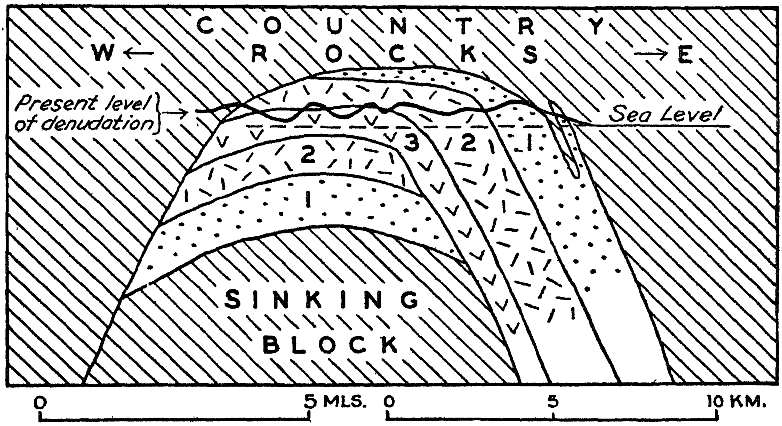

FIG. 97.—Intrusion of the Mourne granites *1*, *2*, and *3* by successive sinkings of a block of country rock bounded by a ring fracture. (*According to J. E. Richey, Quart. Jour. Geol. Soc. London, vol.* 83, 1928, *p.* 685.)

These instances, though themselves perhaps in no true sense actual samples, point to the possible reality of what may be called *ring-fracture stoping.*

The last chapter bore a reference to a still more imposing disturbance, *major stoping,* where much larger sections of the earth's crust, broken apart by the orogenic process, founder in the substratum. Their engulfment is threatened, no matter whether the fracturing of the crust results from the earth's contraction or from the forceful migration of continents.

[1] H. K. Cargill, L. Hawkes, and J. A. Ledeboer, Quart. Jour. Geol. Soc. London, vol. 84, 1928, p. 521.

[2] J. E. Richey, Quart. Jour. Geol. Soc. London, vol. 83, 1928, p. 685. *Cf.* J. E. Richey and H. H. Thomas (*ibid.*, vol. 88, 1932, pp. 776, 843).

Thus magmatic stoping cannot be adequately treated without recognizing the possible importance of

1. Piecemeal stoping, especially downstoping.
2. Ring-fracture stoping.
3. Major stoping.

Transitional types may be looked for.

Xenoliths of shale seem to have been stoped *up* in the minettic magma at Yogo Canyon, Montana (Fig. 98). Lewis suggested the possibility of "underhand stoping" by the Palisades sheet of New

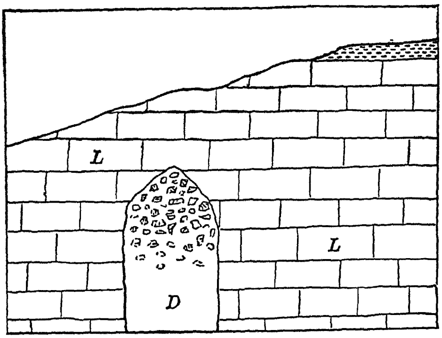

FIG. 98.—Section of top of a sapphire-bearing minette dike (1 to 2 meters wide) in the wall of Yogo Canyon, Montana. According to W. H. Weed (20th Ann. Rep. U. S. Geol. Survey, part 3, 1900, p. 456), the blocks of shale and limestone indicated within the dike were upstoped. *L*, limestone; *D*, dike.

Jersey.[1] Walker regards upstoping as probable in the western sill of the Shiant Isles.[1]

On a much larger scale upstoping appears to have been performed by the noritic magma of the Bushveld Complex, extensive slabs of the Transvaal system of sediments having floated up some thousands of feet from the floor of the sheet, to come to rest near the base of the overlying granitic phase.[2]

[1] J. V. Lewis, Ann. Rep. State Geologist of New Jersey for 1907 (1908), p. 132. F. Walker, Quart. Jour. Geol. Soc. London, vol. 86, 1930, p. 362.

The expression "overhead stoping" is preferred to its synonym "overhand stoping," as better declaring the actual process in magmatic chambers. For the same reason "upstoping" or "floor stoping" seems more appropriate than "underhand stoping."

[2] See R. A. Daly, Bull. Geol. Soc. America, vol. 39, 1928, p. 767. Of course stoping through differential density is not the only cause for the vertical displacement of xenoliths during the life of the inclosing magma. From a discussion of the inclusions in dikes by S. Powers (Jour. Geol., vol. 23, 1915, pp. 1, 166) it is clear that some xenoliths are passively dragged by magmatic currents to levels where they would not have remained if relative densities alone were in control and the magmatic viscosity and ultimate crystallization had not prevented the sinking of the xenoliths.

Formation of Shatter Blocks (Xenoliths)

The experienced student of batholithic masses is familiar with belts of country-rock inclusions, exposed just inside the main (roof and wall) contacts. Normally such a shatter belt of xenoliths is not

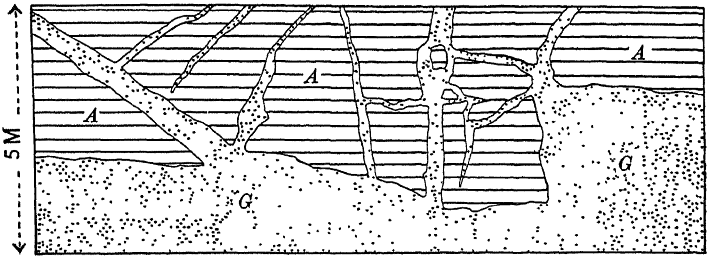

Fig. 99.—Arrested stoping at the roof of the Lausitz granite batholith; quarry exposure. *A*, andalusite-mica rock (hornfels); *G*, granite. (*After R. Lepsius, Geologie von Deutschland, Teil* 2, *Stuttgart,* 1903, *p.* 194.)

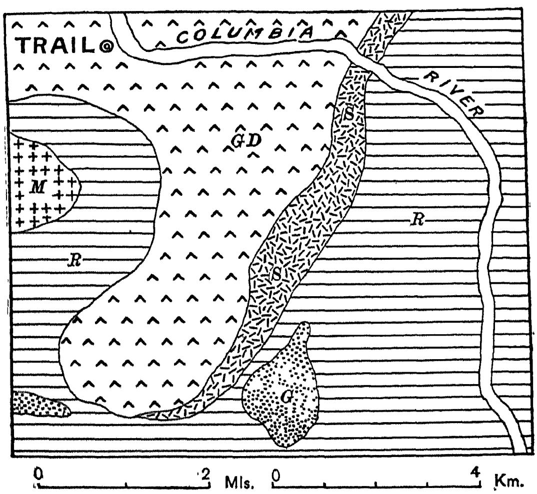

Fig. 100.—Shatter zone (*S*) at the contact of the Trail batholith, British Columbia. *R*, Rossland volcanic series and older formations; *M*, monzonite stock; *GD*, granodiorite batholith; *G*, granite stocks. (*Mem. 38, Geol. Survey Canada,* 1912, *p.* 349 *and map sheet* 8.)

to be mapped as clearly separate from an external belt of the country rock, which along the main contact is riven with many apophyses in the form of dike networks (Fig. 99). An example of the internal shatter belts is illustrated in Fig. 100. Another has recently been mapped by Guernsey.[1]

[1] T. D. Guernsey, Summ. Rep. Geol. Survey Canada, 1927, part C, map 223A. For a discussion of shatter belts see R. A. Daly, Amer. Jour. Science, vol. 16, 1903, pp. 110–125, and "Igneous Rocks and Their Origin," footnote, p. 201.

The cause of this disruption of the country rock is a problem of some difficulty. Where the brecciation is largely confined to the immediate vicinity of the igneous invader, it is logical to look for explanation in the magma itself and to suspect that marginal shattering may be magmatic shattering. Accordingly, the magma would have been active, not a mere passive material moving under purely external forces.

Two causes for the breaking tensions are naturally conceived: the tendency of the batholithic liquid to exert bursting pressure on the roof, and differential heating of the intruded rock.

On account of the low density of granitic and other silica-rich magmas, isostatic adjustment is likely to cause outward pressure from the chamber of liquid. In fact, a few authorities believe the larger granitic intrusions to have domed their roofs to some extent.[1] Although doming by such upward, hydrostatic pressure may account for but a small part of the space occupied by a typical batholith, it should stretch the roof. With sufficient stretching, the rocks necessarily break. Moreover, for a considerable distance below the roof, the wall rocks are under lifting tension and thus subject to apophysal injection. In Chapter XI we saw that even a feeble hydrostatic pressure on the liquid of a sharply terminated apophysis must produce great tensional or ripping stress at the bladelike edge of the injection, so that, while the liquid pressure persists, the dike continues to prepare its own way through the country rocks. The advance is facilitated by joints and other planes of weakness. Partly for this reason the magmatic offshoots have much irregularity of trend, both vertically and horizontally. Where the twisting apophyses, still liquid, cross one another, blocks of the country rock may become completely surrounded by liquid and thus liable to stoping, as well as to inclosure through frictional dragging by magmatic currents.

How closely Barrell agreed with these deductions is shown by the following quotation:

> The rise of magmas from abyssal depths would appear to result from the unbalancing of a hydrostatic equilibrium. The liquid column is lighter than the surrounding rocks. As the liquid rises above the datum plane where the liquid and solid are under the same pressure, the internal pressure at any level is diminished by the weight of the column of liquid below; the pressure in the surrounding rocks is diminished by the greater weight of the rock column between the level and the datum plane below. A bursting and intruding pressure is consequently developed. In the zone of flowage the thick cover

[1] *Cf.* W. Lindgren, Problems of American Geology, New Haven, 1915, p. 284; H. Cloos, Das Batholithenproblem, in Fortschr. d. Geol. u. Pal., Heft 1, 1923, p. 11; J. Barrell, Amer. Jour. Science, vol. 1, 1921, p. 6.

would permit this internal pressure to act laterally, pushing the walls aside. Injection into the roof in steep foliation planes also implies a lateral distension. More or less doming of the cover is of course also to be postulated.

When a large magmatic body has advanced, however, comparatively near to the surface, a lateral distension of the walls or cover becomes subordinate, because the line of least resistance is now for the magma to dome the cover upward, to produce intrusion fractures, and to intrude in distinct sheets and dikes, rather than to produce a *lit-par-lit* injection. The mechanical conditions making stoping a dominant process are then found especially in the zone of fracture; those making for injection, mashing, and crystallization with lateral distension of the wall rocks prevail in the zone of flow. The Black Hills granite belongs to the Pre-Cambrian. In these ancient batholiths crustal distension by the invading magmas appears to have been a dominant process, though stoping even here may have participated. The far younger batholiths of the Cordillera were intruded to high levels and with more or less absence of compressive forces. In these stoping appears to be a dominant process in the higher stages of their invasion.[1]

The conditions so far described seem insufficient to explain the intensity of the shattering along many plutonic contacts, such as that

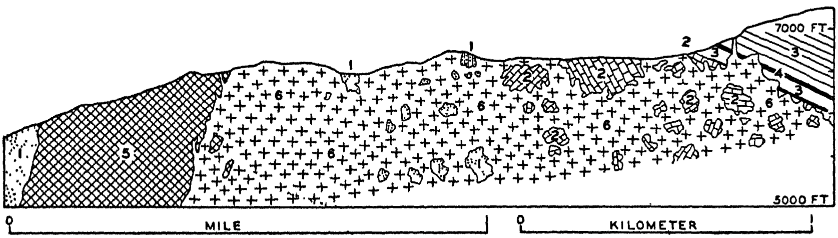

FIG. 101.—Section of monzonite stock, Tintic district, Utah, showing large xenoliths of wall and roof rocks, stoped down but finally held at relatively high levels by the freezing of the magma. *1*, Cambrian quartzite; *2*, Cambrian dolomite; *3*, Ordovician limestone; *4*, Ordovician quartzite; *5*, Tertiary rhyolite; *6*, Tertiary monzonite. (*After G. F. Loughlin, Prof. Paper* 107, *U. S. Geol. Survey*, 1919, *Plate* 5.)

illustrated by Fig. 101. To account for much of this underground brecciation, we may appeal theoretically to the thermal effect of the magma.

As a starting point we adopt the natural supposition that a magma of batholithic proportions is, for a long time, stirred by currents. Under that condition the solid rock at the contact becomes heated nearly or quite to the magmatic temperature. Farther away the heating is much less rapid. To compute the temperature gradient established at the end of a given period, we need to know the average diffusivity of the wall rock, its original temperature, and the initial temperature of the magma. If the temperature of the wall rock be

[1] J. Barrell, Bull. Geol. Soc. America, vol. 27, 1916, p. 105.

taken as 400°F. (corresponding to an average depth of about 29,000 feet or 9000 meters), the temperature of the well-stirred magma as 2200°F., and the diffusivity as 400 (the value used by Kelvin), the temperatures of the rock at various distances from the contact would, at the end of 1, 4, 16, and 100 years, have the values stated in Table 34.

TABLE 34

Distance, feet	1 year	4 years	16 years	100 years
0	2200°F.	2200°F.	2200°F.	2200°F.
10	1703	1947	2074	
20	1263	1703	1947	
40	683	1263	1703	
80	408.5	683	1263	
100	*ca.* 400	537	1078	1703
160	400	408 5	683	
200	400	*ca.* 400	537	1263
320	400	400	408.5	
400	400	400	*ca.* 400	683

At the end of the first year the temperature of the rock 80 feet from the contact is but little affected by the magmatic heat, and the temperature gradient for the 80-foot shell then averages nearly 23° per foot. At the end of four years the rock 160 feet from the contact would still have nearly its original temperature, and the corresponding gradient to the contact is about 11° per foot.

Kelvin's value for the diffusivity is too high, and the actual thermal gradients in the country rocks would be steeper than those just described. The wave of heat from plutonic magma is seen to progress with great slowness; the resulting gradient must be steep for many years after the original establishment of the contact.

The stresses produced by this differential heating can hardly fail to break and exfoliate the country rocks. If the rocks differ in thermal conductivity, the tendency is enhanced. If they are stratified or schistose, it becomes still stronger, for a layered rock conducts heat at rates varying with the direction of heat flow in relation to the layering. The conductivity may be 50 per cent greater along cleavage planes than across them (see page 61).

Possibly also the change of volume of quartz grains when these undergo inversion with heating may be of some importance in magmatic shattering.[1]

Finally, strong stress-differences are expected where the water content of the rock varies from bed to bed, for the gas tension should be great in such a trapped volatile.

[1] See A. L. Day, R. B. Sosman, and J. C. Hostetter, Amer. Jour. Science, vol. 37, 1914, p. 34.

For several reasons, therefore, the shell of country rock becomes packed with tensions. These slowly accumulate until the shell "flies to pieces," like a Rupert's drop suitably scratched.

Richardson has offered objections to the hypothesis of thermal shattering.[1] He believes that "thermal stoping," if the true process, should give smoother contacts than those actually observed in subjacent bodies. The facts are that very many of these interfaces are smooth and "flowing" for great distances; and, second, that, because of the heterogeneity of the invaded formations, because of the differential concentration of magmatic gases (fluxing agents), and because of the complexity of the system of strain, one must expect both cupolas and roof pendants in a subjacent body. In other words, thermal stoping should tend to produce smooth contacts for limited stretches of main contacts, but embayed contacts when roof or wall as a whole is considered.

Richardson's second objection: since the hypothesis does not provide for alternation of temperatures, it cannot account for the observed exfoliation of roof and wall. This batholithic effect is thus supposed to be homologous with the ordinary exfoliation of rock by weathering. However, the relation is not one of homology, but rather one of mere analogy with exfoliation in deserts and other regions of pronounced range of temperature. Truly the suggested brecciation of deeply covered country rock by slow, continuous, one-sided heating is a process less easily visualized than the breaking of rock by rapid changes of temperature at the earth's surface. Nevertheless, no better explanation of much of the contact shattering seems yet to have been published.

Major Stoping

The idea of major stoping implies the coarse brecciation of the whole crust of the earth. In the last chapter we saw that extensive horizontal displacement of the Sial during mountain building of the first class implies foundering of the crust in the orogenic belt. There the crust was necessarily sheared through and presumably fractured in a complex way. Some abyssal injection of the substratum basalt was inevitable. In order to account for the actual mountain chain, complete immersion of blocks of the crust at the orogenic belt and their ultimate subsidence in the less dense substratum are assumed. This orogenic shattering of the crust would be on a much greater scale than that represented along batholithic contacts.

Cloos and his followers emphasize orogenic shattering but do not take seriously the idea of the downstoping of the blocks so formed.

[1] W. A. Richardson, Geol. Mag., vol. 60, 1923, p. 124.

The larger blocks correspond to the *Schollentektonische Elemente* of Cloos, with the difference that necessary solid-elastic support of the *Elemente* is not postulated, as in the Cloos hypothesis.[1]

Richardson has suggested a different kind of orogenic shattering, with magmatic stoping on a big scale. He supposes the stage of tangential compression causing a mountain chain to be followed by a "reaction." The reaction leads to "reversal of the shear" below an intracrustal level and to the development of breaking tensions below that level. The thick masses of crust rock, so pulled apart, then founder in the substratum, their places being taken by great bottomless bodies of magma ("batholiths"). The cause of the reaction is not clear; if it be a characteristic of orogeny, the results might be as drastic as those involved in the "major" stoping above described.[2]

Relative Densities of Xenolith and Magma

We shall now consider the range and sign of the difference of density between xenolith and inclosing magma, the latter having in solution no more than the normal small proportion of volatile matter.

Based chiefly on the experimental work of Douglas and of Day, Sosman, and Hostetter, Table 35 has been constructed. It shows the approximate specific gravities of crystalline rocks and their respective

Table 35.—Specific Gravities of Rocks and Glasses
(Atmospheric pressure)

Groups	Crystalline rock at			Equivalent glass at		
	20°	900°	1100°	20°	1100°	1200°
Group A: gabbro, diorite	2 80	2 74	2.73	2 63	2 53	2.52
	2 90	2.84	2.82	2.73	2.63	2.62
	3 00	2.94	2 92	2 82	2.71	2.70
	3 10	3.03	3 01	2.91	2.80	2.79
Group B: quartz diorite, syenite	2 70	2.61	2 59	2.51	2.41	2.40
	2 80	2.70	2 69	2.60	2.49	2.48
Group C: granite, gneiss	2.60	2 50	2.48	2.34	2 27	2.26
	2 70	2.60	2.58	2.43	2.35	2.34
	2 80	2.70	2 67	2 52	2.44	2.43

glasses at various temperatures. For the present purpose it has seemed best to be conservative and assume the percentage decreases of specific gravity in passing from crystalline rock at 20°C., to glass at 20° as, respectively, 6, 7, and 10 for the three groups of rocks, A, B, and C, Table 35 (see also page 49).

[1] H. Cloos, Der Erongo, Beitr. z geol. Erforsch. d. deut. Schutzgebiete, Heft 17, 1919, p. 187.

[2] W. A. Richardson, Geol. Mag., vol. 60, 1923, p. 126.

The mean coefficients of expansion of the materials (per degree Centigrade and at atmospheric pressure) were assumed to be:

	Group A	Group B	Group C
For crystalline rock	25×10^{-6}	40×10^{-6}	45×10^{-6}
For equivalent glass	35×10^{-6}	40×10^{-6}	30×10^{-6}

Table 36 gives the approximate changes of specific gravity undergone by blocks of stratified and schistose rocks (common country rocks about batholiths), as these blocks, regarded as still solid, take on the temperature of magma in which they are immersed. For all the solid rocks the same coefficient of expansion, 50×10^{-6}, is assumed. Corresponding values for igneous rocks, which are abundant in roofs or walls of batholiths, are to be found in Table 35.

TABLE 36.—SPECIFIC GRAVITIES OF HEATED ROCKS

Rock	Range of specific gravity at 20°	Range of specific gravity at 1100°
Gneiss, mica schist	2.60–3 10	2.47–2 94
Sandstone	2.20–2.75	2 09–2 61
Argillite	2 40–2 80	2 27–2.66
Limestone	2.65–2 80	2.51–2 66

SINKING OF XENOLITHS, MINOR AND MAJOR

At depth in the earth the compression of rock or melt increases the density, though but slightly until the depth exceeds 50 kilometers. Since the compressibility of a crystalline rock is nearly the same as that of its melt, the ratios of density implicit in Tables 35 and 36, computed for one atmosphere of pressure, apply in principle even for rocks and magmas at depths as great as 100 kilometers.

Thus, nearly all xenoliths sink in molten granite or syenite; most xenoliths sink in molten quartz diorite, tonalite, or acid gabbro; many xenoliths might float in basic gabbro, but the denser schists and gneisses must sink in even the denser gabbroic magmas. Most of the blocks shattered from wall or roof should sink if immersed in batholithic magmas of the prevailing types.

In relation to major stoping the conclusions are parallel. Blocks of the Simatic crust, under the oceans, would certainly founder if immersed in the vitreous substratum. Blocks of average Sialic rock have a density *in situ* nearly equal to the density of the substratum *in situ*, but, if they were immersed in it at any depth below the 50-kilometer level and accordingly compressed, they would probably sink. Such would be the actual fate of blocks of the entire continental crust and, still more clearly, of blocks broken from the lower half of the

continental crust, even if these should arrive at levels where the vitreous Sima is considerably more femic than plateau basalt.[1]

Cloos, Kayser, and a few other geologists believe the viscosity of granitic magmas to be too great to allow sinking of blocks even considerably denser than those liquids. This view is not supported by physical experiment or by field evidence. The sinking is inevitable as long as the viscosity is finite; if it is infinite, the "magma" is a true solid. Doubtless, silicate liquids become true solids when undercooled sufficiently, but these glasses do not represent what petrologists have to regard as the condition of granitic magma. The xenoliths visible along batholithic contacts have assuredly not sunk far from their former positions in wall or roof, and the reason is not only the high viscosity of the magma at a late stage of its cooling but also the ultimate attainment of true strength with crystallization, if not with undercooling. No student of magmatic differentiation can question the prolonged mobility of plutonic magma in general. Even rhyolite covers many square kilometers with a single thin sheet. The absolute viscosity of the Yellowstone Park rhyolites must have been comparatively low when those long flows were erupted. According to a verbal statement by Professor E. S. Larsen, the same conclusion applies to the extended flows of rhyolite in Colorado.

In Chapter V we noted the range of viscosity shown by standard substances. With the figures in mind we glance at the results of some experiments. After a few days or weeks, stones are seen to have sunk through, and corks to have risen through, a mass of hard pitch, the viscosity of which is more than a million million times that of water. In a few minutes, small steel spheres will sink through 20 centimeters of Venetian turpentine, a substance 100,000 times as viscous as water. Ladenburg's experiments verified the Stokes equation that gives the rate of sinking of a sphere in a strongly viscous fluid:

$$x = \frac{2}{9}\frac{gr^2(d - d')}{v},$$

where x = the velocity of the sphere when the motion is steady; g = the acceleration of gravity; d = the density of the sphere; d' = the density of the fluid; r = the radius of the sphere; and v = the viscosity of the fluid.[2]

[1] Some of these deductions would conceivably apply if the vitreous shell were largely of peridotitic composition, for, in melting, peridotite probably expands about twice as much per unit volume as gabbro does.

On p. 197 of "Igneous Rocks and Their Origin" was given the suggestion that the crust in continental sectors is intrinsically less dense than the substratum; the new geophysical and other data now seem to indicate the reverse relation.

[2] R. Ladenburg, Ann. der Physik, vol. 22, 1907, p. 287; G. G. Stokes, Cambridge Phil. Trans., vol. 9, 1850, p. 8.

In a granite magma with the viscosity of hard pitch, a 2-meter sphere of gneiss would sink about 10 centimeters per day. A similar sphere 4 meters in diameter would sink four times as fast. If the sphere were much larger, the Stokes formula would not apply. Allen has developed the formula for the larger spheres:

$$x^2 = \frac{1}{k} \cdot \frac{4\pi}{3} \cdot gr\frac{d - d'}{d},$$

where k is a constant for a given liquid-solid system. The terminal velocity here varies as the square root of the radius.[1]

Other things being equal, then, the rate at which a xenolith sinks is some direct function of its size. This deduction matches the rule in Nature: along batholithic contacts, xenoliths with diameters greater than 10 meters are generally rare, though, of course, roof pendants of indefinite size are found.

Subjacent masses crystallize with extreme slowness, a rate controlled by the low conductivity of rock and melt. Hence the presence of xenoliths at the observed levels betokens for the magma, when it inclosed the foreign bodies, a viscosity much higher than that of ordinary pitch. At the end of the magmatic period the viscosity of any visible batholith approached that of steel. How different the conditions when the magma was mobile enough to permit differentiation or the injection of narrow apophyses into the country rock! During the prolonged liquid stage, many successive shells of roof and wall may have been stoped down without leaving any direct evidence of as many crops of xenoliths. It is surely unwise to try to estimate the stoping process merely by counting the visible xenoliths in intrusive bodies.

Finally, we note the effect of the acidification of any invading basic magma. This chemical change lowers the density of the melt and somewhat offsets the influence of cooling and consequent increase of viscosity on the stoping mechanism.

Many examples of the demonstrated subsidence of xenoliths might be given, but a few will suffice. Calkins describes a block of the Wallace formation which sank thousands of feet in the syenite of Ninemile Creek, Idaho.[2] While an argillaceous xenolith would not be likely to sink in a gabbroic or noritic magma, the same material after strong metamorphism by the magma would sink. Read believes that the xenoliths enriched in magnesia and lime from the noritic magma of the Banff-Huntly region of Scotland did sink in that liquid and were

[1] H. S. Allen, Phil. Mag., vol. 50, 1900, p. 532.
[2] F. C. Calkins, Prof. Paper 62, U.S. Geol. Survey, 1908, p. 72.

absorbed at the deeper levels.[1] Rogers writes of large xenoliths composed of Molteno beds and Cave sandstone, deeply sunk into the body of a big doleritic body in Namaqualand, South Africa. "By collapse of the roof, large blocks of strata became enveloped in the igneous magma and sank to lower levels."[2]

Objections to the Stoping Hypothesis

Cloos believes stoping to be practically unimportant for the problem of batholithic emplacement, giving several reasons besides that of prohibitive viscosity of the magmas. (1) Xenoliths are only "a little denser" than the inclosing salic magma. But all that stoping demands is a little difference of density. (2) The number of visible xenoliths is "too small" to match the hypothesis.[3] This point we have just considered. Is there any necessity that contact shattering should be prolonged after stoping, at a late stage in the magmatic history, has largely cleansed the main contact of a batholith of shatter blocks already formed, especially the bigger blocks?[4] (3) Another argument is founded upon an erroneous idea—that piecemeal stoping is held responsible for the whole uprise of batholithic magma, instead of being responsible merely for the completion of the process. On the contrary, it seems clear that the ascent of the magma must be ascribed chiefly to pure (abyssal) injection of the crust. (4) According to Cloos, the hypothesis proves too much: if it were true, stoping should be at work everywhere, and at all times threatening the integrity of the crust. But there is no reason to assume the required shattering of the crust except along orogenic belts, where, in fact, we have plain evidence of at least some stoping. (5) Cloos, followed by von Wolff, believes the existence of a "paper-thin septum" between the Meissen syenite and the Lausitz granite disproves the stoping hypothesis. The logic of this conclusion is not apparent. (6) A much more serious difficulty, appreciated from the beginning, is discussed in the next section.

[1] H. H. Read, The Geology of the Country around Banff, Mem. Geol. Survey Scotland, 1923, p. 140.

[2] A. W. Rogers, Ann. Rep. Geol. Survey South Africa for 1913 (1914), Pretoria, p. 96. Compare A. L. du Toit's statement of a South African and world-wide method of granitic intrusion—stoping activated by the initial magma itself (The Geology of South Africa, Edinburgh, 1926, p. 45).

[3] See H. Cloos, Der Mechanismus tiefvulkanischer Vorgänge, Braunschweig, 1921, p. 6. The same objection was made by J. F. Kemp, Trans. Amer. Inst. Min. Eng., Feb., 1913, p. 603.

[4] For xenoliths of identical shape but different sizes the shearing stress leading to subsidence increases with the square of the horizontal radius, while the frictional resistance increases in simple proportion to that radius.

ROOF FOUNDERING

How far have magmas thinned the roofs of their chambers by stoping? Have some batholiths so destroyed parts of their roofs? The answer to the second question is suggested by the observations described in Chapter VIII, page 141.

Since early Archean time, roof foundering on a scale greater than that represented at ordinary volcanic pipes seems to have rarely occurred, and this fact needs to be reconciled with the stoping hypothesis. Barrell found here "the greatest theoretical difficulty in the

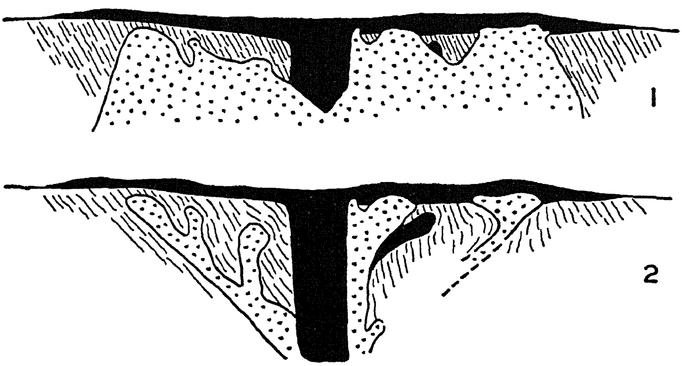

FIG. 102.—Hypothetical sections of the Erongo Mountains, Southwest Africa. *Line shading*, folded crystalline schists. *Solid black*, stock of granodiorite and diorite with extensive equivalent as porphyries. *Dot pattern*, Erongo granite—in *1*, as batholith, in *2*, as branching "discordant laccolith." Length of section, about 40 kilometers. Compare Fig. 61. (*After H. Cloos, Das Batholithenproblem, Berlin,* 1923, *p.* 47.)

way of accepting stoping as one method of batholithic invasion." He pointed out that the same problem arises in connection with any alternative hypothesis.[1]

So it is, for example, with Cloos's interpretation of many granite massifs. He regards these as harpolithic or irregular (chonolithic) bodies, emplaced by pure injection into a crust which was fractured, coarsely brecciated, and strongly domed over each of the intrusions during energetic mountain building (Fig. 102). According to Cloos, this mode of emplacement is "*harmloser*" than emplacement by stoping, but is it? In at least some cases the pure injection of magma with batholithic volume and at the observed levels should have damaged the roofs of the new chambers. Moreover, if the roof under such stress be actually broken into blocks, separated by apophysal magma reaching the surface, the blocks are liable to founder.

The abundance of effusive quartz porphyry and allied lavas in the Archean terranes, such as that of Scandinavia, suggests that the

[1] J. Barrell, Prof. Paper 57, U.S. Geol. Survey, 1907, p. 172.

foundering of roofs may have been not uncommon when the earth was young.[1] Its rarity during later eras may be plausibly referred to the gradual thickening of the crust. In any case magmatic stoping is a cooling process, and thermal shattering probably takes place at the expense of heat in the original magma; sufficient cooling prevents further thermal shattering, and ultimately the magmatic viscosity becomes too high for stoping. The integrity of the batholithic roof is no longer threatened.

Further, the foundering of a part of the roof can take place only after that part has been severed from its initial solid-elastic connection with the rest of the earth's crust and thus becomes horizontally surrounded, as well as underlain, by magma. Such a condition demands appropriate, nearly or quite simultaneous diking along all sides of the threatened block. Of course, this is theoretically possible. However, since a dike freezes solid with comparative rapidity and thereby tends to heal the crust quickly, the actual isolation of a complete segment of the roof is not easily accomplished. This principle would apply even to the case where the roof as a whole is under moderate horizontal tension, a tension which is likely to be relieved slowly, step by step, through fracturing and diking. For here too the integrity of the roof is restored as each dike or dike swarm freezes solid. That the roofs of batholiths, still molten, were under general horizontal tension is at least a question for debate. If, as some geologists believe, batholithic roofs were normally under mild horizontal compression during the magmatic period, the chances of foundering were still smaller.

One cause tending to give such compression, and hence greater stability for the batholithic roof as a whole, is the heating of that roof by the magma. As far as it goes, the resulting expansion of the rocks and tightening of the roof work against the easy development of throughgoing dikes, with associated danger of isolating in the liquid blocks with the full thickness of the roof.

To summarize: Roof foundering as well as crust foundering may have been a common event during the long process of developing the Archean complexes. More recent foundering of batholithic roofs has been decidedly rare. Why this should be so is a question as yet without definitive answer. The most promising solution to the "problem of the cover" seems likely to be founded on the assumptions that the finishing of the emplacement of a batholith demands much heat, and that the earth has long been too cool to supply batholithic magma with heat enough to endanger the integrity of the roof except on rare occasions.

[1] *Cf.* also F. von Wolff, Handbuch der Geophysik, ed. by B. Gutenberg, Berlin, vol. 3, Lief. 1, 1930, p. 173.

The *replacement* of invaded formations by piecemeal stoping at roof and wall is illustrated in Chapter VII (Figs. 39, 40, 43, 49, and 52). The example at Marysville was described by Barrell with consummate

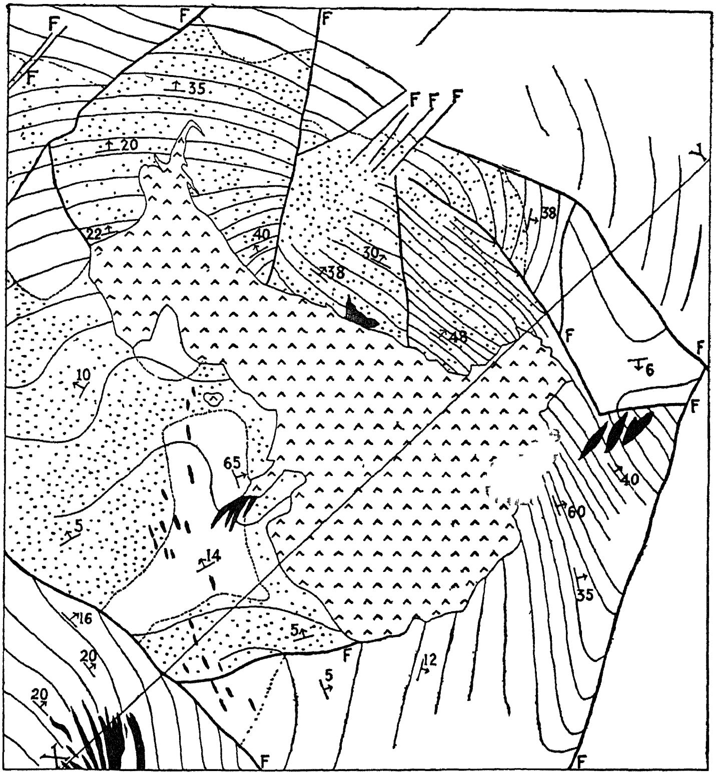

FIG. 103.—Map of the quartz-diorite stock (*carets*) at Marysville, Montana. *Stipple*, Empire shale, *blank*, Helena limestone; *solid black*, diorite, microdiorite, and diorite porphyry; *F*, faults; *thin lines*, strike contours with 250-foot interval. Dips in degrees. Scale, 1:62,000. Note crosscutting igneous contacts and general evidence of magmatic replacement. (*After J. Barrell, Prof. Paper* 57, *U. S. Geol. Survey*, 1907, *p.* 74 *and map in pocket.*)

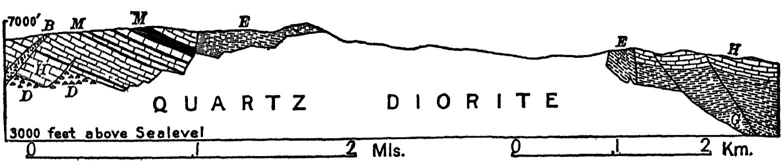

FIG. 104.—Section along the line *X–Y* in Fig. 103. *G*, Greyson shale; *M*, microdiorite; *B*, Belmont diorite porphyry; *D*, diorite. Note stoping reentrants in the roof of the stock, and the peripheral position of the diorite.

science and art (Figs. 103 and 104). Almost all subjacent bodies give proof of the process, though only a part of its whole effect can

there be demonstrated (Figs. 105 and 106). This limitation of convincing evidence is in part naturally due to the sinking of xenoliths to invisible depths.

Few concordant intrusions exhibit much marginal shattering or proofs of stoping. Among the reasons are the following: the relatively small amount of thermal energy possessed by these bodies, the expected inability of their magmatic currents to raise the country

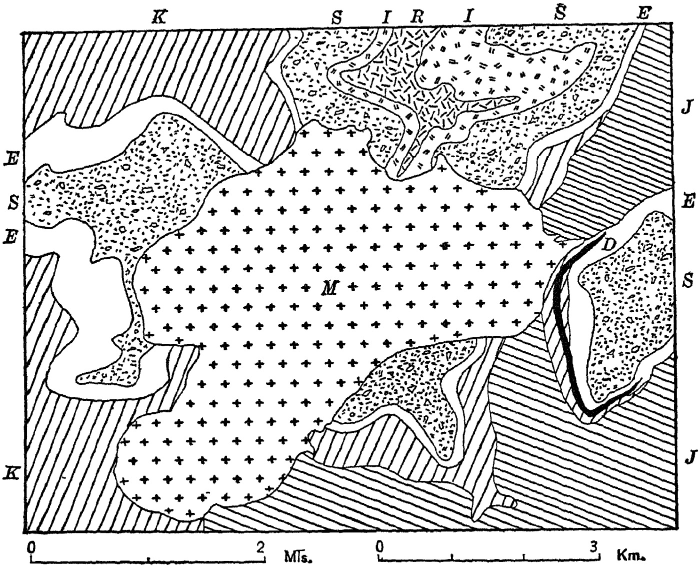

FIG. 105.—Map of monzonite stock in the Telluride quadrangle, Colorado, showing crosscutting character. *M*, monzonite; *D*, diorite porphyry; *R*, Potosi rhyolite; *I*, Intermediate series (volcanic breccias); *S*, San Juan tuffs; *E*, Eocene conglomerate; *K*, Cretaceous shale and sandstone; *J*, Jurassic shale, sandstone, and limestone. *M*, *D*, *R*, *I*, and *S* are Tertiary; the monzonite cuts all the bedded rocks. (*After the Telluride folio, U. S. Geol. Survey*, 1899.)

rock nearly to the initial temperature of the magma, and the high viscosity of these magmas either at the beginning or soon after injection. If considerable viscosity determined the shape of the more bulbous laccoliths and betokened short magmatic life for these small masses, it is clear why they were not able to do much stoping; though some thinner but less viscous sills did shatter and stope fragments from their roofs. Illustrations appear among the Purcell sills of British Columbia, in the Pigeon Point sill of Minnesota, and in the Sudbury sheet of Ontario.[1]

Fate of the Downstoped Blocks

A principal corollary of the hypothesis is chemical change of the magma receiving sunken xenoliths, large and small. Since the magma

[1] R. A. Daly, Amer. Jour. Science, vol. 20, 1905, pp. 194–208.

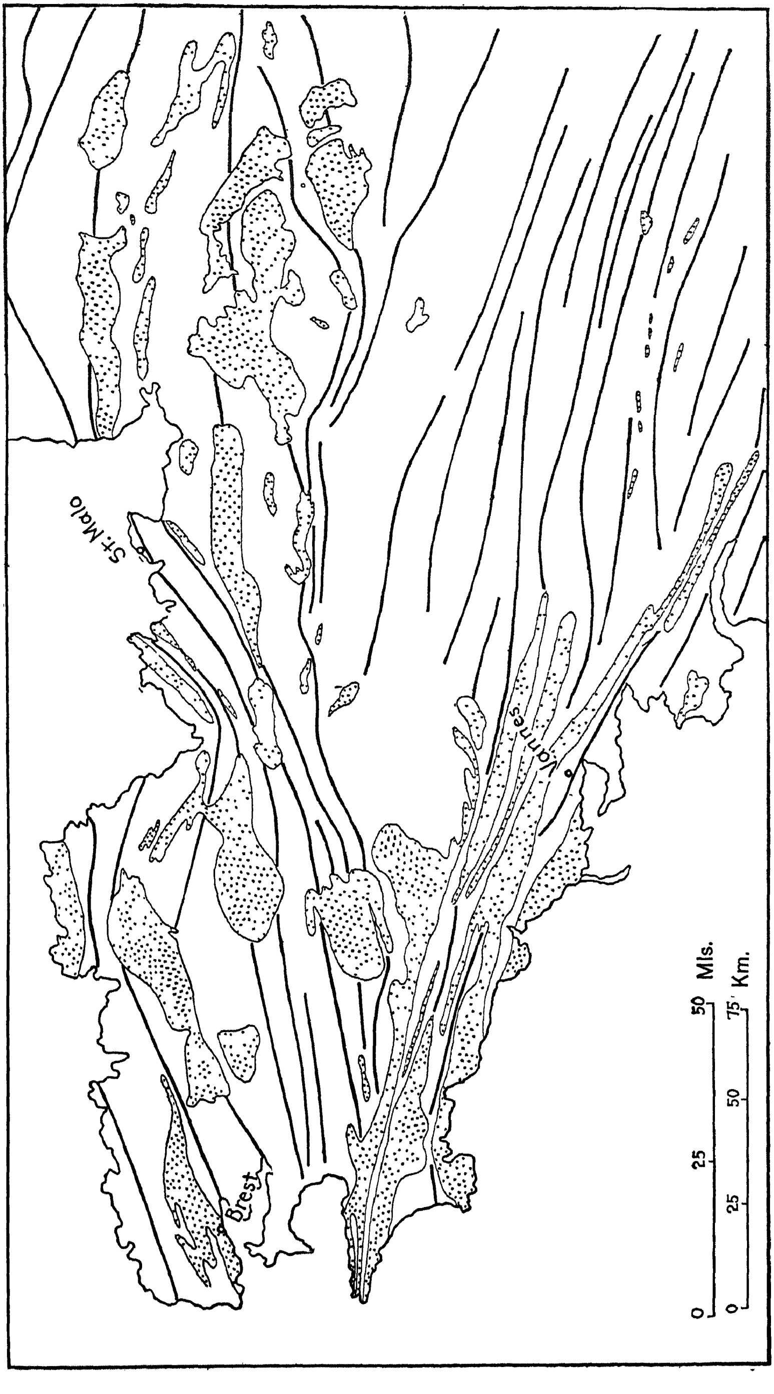

FIG. 106.—Map showing distribution of stocks and batholiths (*dotted*) in Brittany; orogenic axes shown by heavy lines.

is hotter at depth than at roof and wall, we may well expect some pure melting and solution of at least the more fusible parts of the inclusions. The next chapter will discuss that idea in some detail. For the moment we note it more particularly because it suggests another test of the stoping hypothesis itself.

The average wall rock within the Sialic shell is chemically granitic or granodioritic. By pure melting and true assimilation the primary basalt of abyssal wedge or even the substratum beneath itself becomes charged with more salic material. According to the principle of gravitative differentiation, the importance of which will be abundantly illustrated hereafter, the new, more acid melts rise toward the roof. They rise as such, or after the differentiation of the xenolith-basalt mixtures. In general, then, great batholiths should be, at their upper levels, of granitic or closely allied composition. The next and following chapters will show how well this test of the stoping idea is actually met.

Conclusion

The stoping principle was made familiar to geologist and geophysicist by Lord Kelvin, who pictured many successive founderings before the crust of the young earth became stable. Since Archean time such general stoping appears to have been prevented for several reasons, particularly because of the strength of the crust. The results of local piecemeal stoping are manifest in batholiths, stocks, and thick sills. Ring-fracture stoping and major stoping are ideas of another order, both being products of deduction and therefore requiring special scrutiny. They too are local and apparently confined to orogenic belts. All three types of crustal replacement are dependent upon density relations that are more or less clearly demonstrated. In combination with the principle of abyssal injection, piecemeal and major stoping seem to give the best explanation of chief characteristics of subjacent bodies. As outlined in Chapter VII, these features include location in orogenic belts, elongation parallel to tectonic axes, intrusion after orogenic paroxysms, crosscutting relation to the country rocks, the existence of roof pendants and cupolas, downward enlargement, and the general absence of signs that the intrusions made their way by pure injection. Still another way to try the strength of the stoping hypothesis is to see, if possible, what happens to blocks of rock foundered to great depths. Such further examination will be made on later pages.

CHAPTER XIII

PURE MELTING AND MAGMATIC ASSIMILATION OF ROCKS. ABYSSOLITHS

Introduction

Some authorities find in magmatic differentiation the sufficient cause of the variety of igneous rocks. These writers assume either (1) the fractionation of local pockets or reservoirs of primordial magma, or (2) the fractionation of local remelts in an essentially crystalline earth. A third possibility is conceivable: the fractionation of the substratum basalt where this primary vitreous material had been injected into the crust.

Differentiation of liquids never before crystallized cannot be the whole story. Remelting of solid rock and also its solution in magma have been by no means uncommon, especially in the Archean terranes. Hybridism persists notwithstanding the strong tendency for such mixing to be masked by later processes. Usually these have advanced so far as to prevent direct measures of the power of magma to melt or dissolve foreign rock. Hence that power cannot be evaluated by field observation alone; the problem must be treated more or less indirectly. The general principles affecting it are now to be sketched, but many of the relevant facts are reserved for later statement (Chapters XVI to XXII).

First, emphasis will be placed on the pure melting of rocks, a subject hitherto much neglected in textbooks of petrology. We shall then consider the effects of magmatic assimilation. Though differentiation is a reversible process, the believers in the almost exclusive role of differentiation, like Rosenbusch, Vogt, Harker, Iddings, Pirsson, Washington, and Bowen, have regarded assimilation as quantitatively of little moment. On the other hand, its more or less notable influence on the development of magmas has been deduced by Kjerulf, Sederholm, Eskola, Sobral, Fouqué, Michel-Lévy, Lacroix, Barrois, Cotta, E. Suess, F. E. Suess, W. Penck, Kaiser, Erdmannsdörffer, Hibsch, Milch, Loewinson-Lessing, Molengraaff, Johnston-Lavis, Holmes, Brammall and Harwood, Read, Watt, Andrews, Dixey, Hall, du Toit, Wagner, Lawson, Barlow, Brock, Coleman, Collins, Ellsworth, Barrell, C. N. Fenner, W. J. Miller, Waters, Buddington, Daly, and

many others. Long ago Brögger saw plainly the slightness of magmatic assimilation at visible contacts of post-Archean eruptives, but has been careful to admit the possibility of much solution of solid rock at great depth. After an unusually comprehensive review of the subject, Milch agreed with this conclusion of Brögger.[1]

Definitions

A note on the use of terms may help to make clearer the following argument.

"Pure melting" is self-explanatory. It gives secondary magma; the minerals of the solid rock are mutually dissolved, without the aid of foreign fluxes.

"Magmatic assimilation" is the mutual solution of magma with solid rock, with other magma, or with foreign gas, so that a new magma with at least some approach to chemical homogeneity results. Its effects grade into those of pure melting and are probably much enhanced by it.

"Syntexis" is here adopted as a general term to include both pure melting by the heat of adjacent incorporating magma and also assimilation of foreign material by magma.

"Incorporation" may be conveniently used in a broad sense to cover (*a*) true solution of foreign material in magma, (*b*) the mixing of magma and the xenolithic (steadily solid) products of the magma's reactions with country rock, and (*c*) the inclusion of the product of pure melting in the primary magma that supplied the heat of fusion.

"Contamination" is the chemical change of a magma, due to the solution of foreign material, solid, liquid, or gas.

According to Holmquist, the high temperature during metamorphism has led to the development of secondary, pegmatitic magma in place, without eruption from lower levels. Such locally generated liquids thus represent cases of "selective solution" (Lane), the quartz and feldspar of the heated crust rocks being in quasi-eutectic proportion and able to dissolve—liquefy—each other.

Sederholm's "anatexis" (literally, "melting-up") "corresponds to *re-fusion,* although in some cases *re-solution* would be more appropriate."[2] He believes the chief cause of refusion of the Archean rocks to have been the intimate invasion by intensely penetrating, granitic

[1] W. C. Brögger, Die Eruptivgesteine des Kristianiagebietes, Oslo, vol. 3, 1898, p. 350. L. Milch, Jahresber. Schles. Gesell. f. vaterl. Cultur, January, 1903, p. 5.

[2] J. J. Sederholm, Bull. 77, Comm. Géol. Finlande, 1926, p. 135. Plate 9 of his paper strikingly illustrates Sederholm's idea. In Bull. 58 of the Finnish Commission (1923, p. 130) he describes the anatexis of even a conglomerate occurring in the older Pre-Cambrian.

liquid or "ichor," charged with hot plutonic gases ("emanations") from magma in depth. The result of this action was the "palingenesis" (literally, "rebirth") of granitic and allied magmas; "the rock in question has been reborn, in other words received a new eruptivity." However, palingenesis seems to be a term broad enough to cover the case of pure melting, through mere rise of temperature and without the introduction of foreign gases.[1]

Pure Melting of Rocks

Divers opinions have been expressed concerning the relation of mere melting to the generation of igneous rocks. T. C. Chamberlin assumed the earth to be essentially crystalline throughout and explained magmas as products of selective fusion at great depths. Joly postulates wholesale periodic refusions of a general, basaltic earth shell through radioactivity. Lawson leapt into fame when he announced the palingenetic origin of the Laurentian granites of Canada (refusion of the pre-Keewatin terrane). Scandinavian geologists hold the same general conception as explaining part of the Archean granites of Fennoscandia. Fermor writes of the remelting of the pre-Dharwar crust in India as a principal step in the formation of the "fundamental gneiss" of the peninsula. Some petrologists refer individual bodies of magma to the remelting of crystalline material because of the relief of pressure. Haug has had a few followers in postulating pure melting on the large scale, brought about by deep (geosynclinal) burial. Without describing the cause, Jung has suggested that the Miocene (subalkaline) magmas erupted along the German-Bohemian foreland of the Alps were generated by the remelting of Carboniferous igneous rocks at depth. According to Cloos, "all rocks melt," if sunk deeply enough, a view also favored by Erdmannsdörffer. Von Bubnoff assumes abyssal remelting of the Sial on the large scale. The same postulate is made by several special students of the early Pre-Cambrian terranes. By the selective fusion of older felsic rocks Holmquist, Lane, Van Hise, and others account

[1] According to circumstances, local melting without significant help from gas contained in the rock may be occasioned by (1) general earth heat, (2) magmatic heat, (3) slow but intense shearing under orogenic stress (?), or (4) quick release of powerful strain in a rock mass. The last mode has been assumed in explanation of the large isolated lenses of enstatite granophyre and some of the much smaller innumerable lenses of "flinty crush rock" in the Vredefort dome (A. L. Hall and G. A. F. Molengraaff, The Vredefort Mountain Land, Verh. Akad. Weten. Amsterdam, Sect. 2, Deel 2, No. 3, 1925, pp. 112 *ff.*). L. T. Nel (The Geology of the Country around Vredefort, Geol. Survey South Africa, 1927, p. 101) states that one of the "dikes" of enstatite granophyre is about 15 kilometers long; none is over 50 meters wide.

for some Archean pegmatites. According to Bowen, "many granitic magmas may have their immediate origin in the remelting, say by deep burial, of a granite derived in more remote times from basic material." He also assumes the selective fusion of a peridotitic earth shell as a possible, if not probable, source of all basaltic magma. Harker writes: "At a deep level in the Earth's crust, where solid and liquid rock are in approximate thermal equilibrium . . . extensive melting may be conceded, and, indeed, must be postulated." Vogt was of the same opinion.[1]

Quite recently Eskola has stressed selective fusion of deeply buried silicate rocks as a preliminary step in the formation of many voluminous granites. He writes:

> Both differentiation (preferably by means of squeezing out from partly crystallized rocks) and palingenesis [largely selective fusion] must have been active in the formation of the earth's outer silicate shell and its arrangement mainly according to the densities. In the most ancient geologic development differentiation should have been the more primary and more important factor while, during later orogenic periods, palingenesis may have played a more important rôle.[2]

The subject bristles with difficulties. Even in those instances where xenoliths have been converted to glass, one cannot easily make sure that extraneous hot gas did not help in the fluxing, as it evidently has done at Kilauea and Katmai volcanoes.[3] Again, proof of vitrifica-

[1] T. C. Chamberlin, The Origin of the Earth, Chicago, 1916, p. 235. J. Joly, The Surface-History of the Earth, Oxford, 1925, p. 89. W. H. Hobbs, Earth Features and Their Meaning, New York, 1912, p. 144. A. C. Lawson, 3d Ann. Rep. Geol. Survey Canada, part F, 1888. L. L. Fermor, Proc. Asiatic Soc. Bengal, vol. 15, 1919, p. *clxx*. E. Haug, Traité de géologie, Paris, 1907, vol. 1, p. 189. H. Jung, Chemie der Erde in Zeit. f. Mineralogie, etc., vol. 3, 1927, p. 337. H. Cloos, Der Mechanismus tiefvulkanischer Vorgange, Braunschweig, 1921, p. 3. O. H. Erdmannsdorffer, Grundlagen der Petrographie, Stuttgart, 1924, p. 34. S. von Bubnoff, Die Gliederung der Erdrinde, Berlin, 1923, p. 50. P. J. Holmquist, Geol. Fören. Forh. Stockholm, vol. 42, 1920, p. 209. N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, pp. 319, 315. A. Harker, The Natural History of Igneous Rocks, New York, 1909, p. 338. J. H. L. Vogt, Skrifter Norske Videns. Akad. Oslo, I Kl., 1930, No. 3, p. 235.

In a presidential address G. A. J. Cole (Rep. Brit. Ass., 1915) said: "When it is asserted that the earth is not hot enough to allow of the melting of one rock by another, I can only reply that such melting has taken place."

[2] P. Eskola, Min. u. Petr. Mitt., vol. 42, 1932, p. 474.

[3] This doubt affects two different instances described by A. Lacroix (Les Enclaves des roches volcaniques, Macon, 1893, p. 563) and C. von John (Jahrb. k. und k. Reichsanstalt Vienna, vol. 52, 1902, p. 141), where blocks of gneiss reaching the size of a cubic meter have been entirely transformed into porous glass by inclosing basalt on its way to the earth's surface. So also at Sakurajima (K. Yamaguchi, Japanese Jour. Geol. and Geog., vol. 6, 1928, Abstracts, p. 2);

tion is hardly possible where, as is generally the case, that change is followed by recrystallization. Third, the proof of pure melting, like that for assimilation, is likely to be obscured because its product tends to be dissolved by adjacent foreign magma, and because this mixture and the pure melt itself may be differentiated from the whole vitreous mass and rearranged within the earth's crust. Such complications must long forbid dogmatic assertions either for or against the idea.

Yet it is well to consider the possibilities. We may begin with the fundamental fact that felsic rocks and also the siliceous-alkaline, residual crystallizations of basic magmas become liquid at temperatures lower than that at which gabbro or holocrystalline basalt becomes liquid. This truth had been recognized by a few petrologists, but recent experiments at the Geophysical Laboratory of Washington have provided quantitative data. The results go to show that granite with only a trace of volatile matter begins to melt at a temperature below 700°, "probably" at 570°. After one week the granite was half melted at 800°, a temperature about 300° below that at which basalt or gabbro is melted in the same proportion.[1]

Hence the heat of a large body of magmatic gabbro or plateau basalt, even without superheat, would melt an ordinary xenolith of granite or common gneiss or highly feldspathic sandstone. The basic magma would melt also the mixture of the more alkaline last-crystallized minerals of a basaltic, gabbroid, or dioritic xenolith. Evidently all these more felsic materials would melt in a large body of somewhat superheated basalt.

The same conditions apply when, during orogeny, the Sial is thrust down, pulled down, or locally made to founder, into the vitreous substratum. There pure melting is facilitated by the high temperature of the substratum (supposed just saturated at the pressure of 17,000 or more atmospheres), by the comparatively small latent heat of felsic rock—probably about two-thirds of that of basalt itself—and by a parallel contrast in the specific heats. True assimilation might well accompany the pure melting, but because, as Bowen points out, "the

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there, during the eruption of 1914, blocks of granodiorite were melted and converted into thread-lace scoria. J. M. Sobral (Contributions to the Geology of the Nordingrå Region, Upsala, 1913, pp. 70, 91, 114, 122, 124) states that many acid xenoliths were "melted" by the heat of diabasic dike magma, but he has not made clear the grounds for his conclusion. In the island of Mull (Mull memoir, 1924, p. 157) the melting of basaltic wall rock by basaltic liquid occupying a volcanic pipe may represent a parallel to the effect of fluxing gas at the active vents of Hawaii.

[1] J. W. Greig, E. S. Shepherd, and H. E. Merwin, Ann. Rep. Director Geophys. Lab. Washington, 1931, p. 77; *cf.* Bull. Geol. Soc. America, vol. 40, 1929, p. 94.

diffusivity of temperature is much greater than the diffusivity of concentration," the foreign rocks would be melted before much of their substance could, by mere molecular diffusion, mix entirely with the primary melt.[1]

The heat of melting is theoretically supplied by the substratum or by its offshoots into the crust. Local chilling tends to crystallize some of the Simatic liquid. Whether this part is to remain solid depends on the amount of reheating by hot gases, by radioactivity, by convective overturn in the substratum, or by depression of the chilled material to deeper levels. Hence the contamination of the basic magma with salic matter may elude ready estimate because of displacements and intermittent actions of different kinds.

A few instances of observed pure melting may be mentioned.

A doleritic sill of Mull has melted pelitic gneiss to the depth of 4 or 5 feet, the melted gneiss (buchite) being then intruded into the surrounding rock.[2] According to Hawkes, quartz porphyry was melted by the granophyre-granite magma of Slaufrudal, Iceland; the temperature inferred was no higher than 970°C.[3] Erdmannsdörffer concluded that a syenitic liquid was generated by the partial melting ("palingenesis") of orthophyric tuffs invaded by gabbroid magma.[4] Knopf describes a Californian 15-foot intrusion as hot enough to have partially melted granite and to give the granitic wall rock columnar jointing. The glass resulting from the fusion is interstitial in the granite.[5]

The rare case where pure melting has been noted at the *floor* of an eruptive sheet is recorded by Laitakari. A Finnish, post-Jotnian olivine diabase (either intrusive or extrusive) has melted older, underlying granite of the Rapakivi type, and this secondary granite has diked the diabase. Close to the contact, itself made unsharp by the heat, the older granite has been recrystallized, with the generation of much micropegmatite. This observation is significant, since micropegmatite appears to be one of the commonest products of assimilation of felsic rocks by basaltic or gabbroid magma.[6]

Sudden chilling partly explains the rarity of pure melting at main contacts. Generally the liquid of the smaller eruptive bodies is little stirred by currents after the visible contacts have been made. At those interfaces the *maximum* temperature attainable by the country

[1] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 276.

[2] E. B. Bailey, Mull memoir, Geol. Survey Scotland, 1924, p. 266.

[3] L. Hawkes, Miner. Mag , vol. 22, 1929, p. 163.

[4] O. H. Erdmannsdörffer, Abhand. Akad. Wiss. Heidelberg, math.-nat. Kl., No. 15, 1930.

[5] A. Knopf. Prof. Paper 110, U.S. Geol. Survey, 1918, p. 75.

[6] A. Laitakari, Fennia, vol. 50, No. 35, 1928.

rock is close to the mean of the initial temperatures of magma and country rock. This maximum can hardly have much exceeded 700°, a temperature too low for the melting of ordinary rocks.

But the temperature of small xenoliths rapidly approximates that of the host magma. Here pure melting may take place but, for the reasons noted above, seldom leaves direct evidence of the change of state.

The few proved cases of pure melting are therefore significant out of all proportion to the volumes of secondary liquid produced. Their chief value for petrology consists in illustrating on the minute scale what shall be the fate of big blocks of the crust if these sink into the substratum.

Magmatic Assimilation

There is one rather general reason for the contrast of views held by two groups of petrologists regarding assimilation. With few exceptions the specialists in Archean geology are convinced of its extensive operation. For them, this much-mooted question was answered in the affirmative long ago. Again with few exceptions, petrologists of little experience with Archean rocks answer the same question in the negative; for them, assimilation is quantitatively unimportant. The second solution to the problem has likewise appealed to those laboratory systematists who have had limited opportunity for work in the field. The difference of view arises from the difference of Archean and post-Archean conditions.

Assimilation during Archean Time.—The thermal gradient is assumed to have had maximum steepness during the early Pre-Cambrian. Archean geology becomes intelligible if the ancient crust was specially thin. The granitic magmas that made repeated regional invasions of the supracrustal rocks were generated probably nearer the surface than were the post-Cambrian magmas of the same type.[1] Just below the surface the isogeotherms of the Archean era were relatively crowded, and gases were emanating from the earth's body at a rapid rate. Both conditions produced or retained the liquid state for rock matter comparatively near the surface. Ascending waves of heat and ascending emanations of gas cooperated, and granitic magma, so prepared by fluxing, rose into the crust. The magmatic invasion took place through a combination of mechanical injection and selective fusion. The granitic juices (the "ichor" of Sederholm) with great penetrative and assimilative power produced widespread anatexis and much hybridism. Cotectic solutions were squeezed out of the heated

[1] *Cf.* J. Barrell, Amer. Jour. Science, vol. 1, 1921, pp. 183, 186; O. H. Erdmannsdörffer, Grundlagen der Petrographie, Stuttgart, 1924, p. 318.

solid rocks as "exudates" and elsewhere formed injected veins or "arterites," so conspicuous in Archean terranes.[1] Such regional anatexis, gas fluxing, and assimilation, together with associated metasomatism, account for much of the observed bewildering complexity of the early Archean rocks.

This sketch of the continent-wide remodeling of the ancient crust is based upon the results of workers on the Basement Complex, and their views are not without support from observations made in some post-Cambrian batholithic provinces. When emphasizing the rise of volatiles as one of the important controls in petrogenesis, Michel-Lévy, Barrois, Lacroix, Termier, Duparc and their predecessors and successors in the French school of thought on this subject have been largely justified. Their essential conclusions have been confirmed by many observers, of whom Sederholm and Fenner may be particularly mentioned.[2]

Assimilation under Post-Archean Conditions.—Post-Archean geology tells a different story. It records little or no regional palingenesis or anatexis near the earth's surface. The small volume of post-Archean pegmatites and their general restriction to orogenic belts show a rate of earth's "sweating" not comparable with that of its vigorous youth. Fluxing by the "earth's originally absorbed gases" does continue but seems to have been long confined to volcanic vents and the roofs of intrusive masses. By the end of Archean time the crust had thickened—to remain thick; the thermal gradient had grown less steep—to remain so. Magmatic invasions became much more localized. Their struggle with cold grew more intense as their eruption depended upon the penetration of a thickening crust. Contact

[1] For explanation of "ichor" (Greek "serum" or "blood of the gods"), "arterite," "exudate," etc., see J. J. Sederholm, Bull. 77, Comm. Géol. Finlande, 1926, pp. 88, 134 *ff*; O. H. Erdmannsdorffer, Grundlagen der Petrographie, Stuttgart, 1924, p. 319.

[2] From the extensive literature references as follows have been selected: A. Michel-Lévy, Bull. soc. géol. France, vol. 7, 1882, p. 857; vol. 16, 1888, p. 102. A. Michel-Lévy, Bull. serv. carte géol. France, No. 9, 1893; No. 36, 1893. A. Lacroix, *ibid.*, No. 64, 1898, and No. 71, 1900. C. Barrois, Ann. soc. géol. du Nord, vol. 12, 1884; Bull. soc. géol. France, vol. 14, 1886, p. 678; *ibid.*, p. 865; Guide 7, Cong. Géol. Internat. Paris, 1900; Compte Rendu, Cong. Géol. Internat. Stockholm, 1910, p. 597. P. Termier, Compte Rendu, Cong. Géol. Internat. Vienna, 1903, p. 585; Stockholm, 1910, p. 587. L. Duparc and L. Mrazec, Mém. soc. phys. et nat. Geneva, vol. 33, part 1, 1898. J. J. Sederholm, Bulls. 23, 24, 58, 77, Comm. Géol. Finlande, 1907–1926; Geol. Rundschau, vol. 1, 1910, p. 126, and vol. 4, 1913, p. 174; Compte Rendu, Cong. Géol. Internat. Stockholm, 1910, p. 573, and Ottawa, 1913, p. 319. C. N. Fenner, Jour. Geol., vol. 22, 1914, pp. 594, 694. T. T. Quirke and W. H. Collins, Mem. 160, Geol. Survey Canada, 1930, p. 96.

chilling more and more inhibited the fusion and assimilation of rocks at levels that could, through erosion, be exposed to observation. Though moderate denudation has uncovered the loci of Archean palingenesis, still deeper erosion has failed to lay bare similarly extensive post-Archean anatectics or syntectics.

Field observations thus seem, on their face value, to prove relative insignificance for post-Archean assimilation. Yet a deeper study of those same observations, coupled with the best available theory of the earth's constitution, warrants doubt.

Loci of Post-Archean Assimilation.—When first studying batholithic and other igneous contacts, the author there noted the general failure of hybridism and, like so many other observers, was long sceptical of syntexis as a notable factor in petrogenesis. With the discovery that the intrusion of subjacent bodies was completed, though, of course, not primarily caused, by stoping, the problem of assimilation took on a new aspect. For blocks stoped down to great depths, even as far as the substratum itself, would be specially liable to remelting and solution. Thus the early prejudice became weakened. Ever clearer became the danger of restricting attention to "observed facts." Direct observations are usually confined to the upper parts of igneous bodies, to what may be loosely called a two-dimensional field. The stoping hypothesis puts automatic emphasis upon the actual three-dimensional character of the problem. Three-dimensional it must be in any case, even at the cost of one's peace of mind—even at the cost of risking the quagmire of speculation about the invisible and intangible. There is, indeed, no other way. By declining Nature's own invitation to think intensely about her third dimension, petrologists have "lost motion" and have held back the healthy progress of their science. What petrology needs is controlled speculation about the depths of the earth.

Thus, according to what appears to be a fair statement of the case, assimilation, like syntexis in general, should be considered as:

A. Xenolithic, the assimilation of the blocks being
  1. High level.
  2. Abyssal: (*a*) intracrustal and (*b*) in the substratum.

B. Marginal (main contact), the assimilation being
  1. High level.
  2. Abyssal: (*a*) above the substratum level and (*b*) along projections of the crust where thrust down into the substratum.

Subsequent erosion may lay bare the high-level loci, where, however, the full measure of the syntectic process is not discernible with ease. Two main difficulties may again be mentioned. First, differentiation of the syntectic magma accompanies, and follows the com-

pletion of, the act of assimilation. Hence the resulting rocks are not the chemically unchanged and readily identifiable products of addition. Second, allowance must be made for displacements of both syntectic and differentiated magmas as such, that is, for staccato injection. The normal result of assimilation should not be an obviously hybrid rock.

For the same two reasons, besides the general inaccessibility of locus, outcrops cannot alone decide the case for or against abyssal assimilation. Manifestly here the only mode of attack is to confront the facts of the outcrop with the best theory of the earth's interior and of the kinds of displacement affecting its material.

Both assimilation and pure melting are affected by a simple principle. Per unit volume the surface of xenolithic rock, exposed to reaction with magma, is at least six times as great as the surface of an equal quantity of plane wall rock or roof rock. This ratio may be thousands or millions to one. Hence contamination with xenolithic material is bound to be more pronounced than contamination at main contacts. The relation is analogous to that shown in pure thermal metamorphism.

However, the condition of visible xenoliths and of their immediate surroundings gives no adequate idea of the total amount of syntexis wrought by a large magmatic body, such as a batholith. The retention of the average xenolith at the comparatively high level where it is now seen, in spite of the tendency to sink deeper, is due to the magma's high viscosity and ultimate attainment of strength in shear. What is the integral effect of stoping and syntexis during the thousands of years of a batholith's life before the stage of inhibiting viscosity was reached?[1]

A granitic magma crystallizes within a temperature range of about 1000° to about 600°. During the prolonged cooling through that range, the liquid may be incapable of dissolving much foreign rock but is nevertheless able to stope fragments from roof and wall. Hybridism at main contacts is therefore seldom to be expected, while, on the contrary, solution of stoped blocks may continue in depth throughout even this late stage of the batholith's life. Because the period of stoping is much longer than the dissolving process, roof, wall, and xenolith are, at the levels of the outcrop, usually free from hybrid shells. Thus the rarity of hybridism does not constitute a valid argument against the view that assimilation is important in petrogenesis.

Finally, although marginal assimilation is a cooling process and tends to close its own career, its effects are increased by currents.

[1] A. Harker (The Natural History of Igneous Rocks, New York, 1909, p. 86), like a number of other petrologists, credits some stoping in subjacent masses but questions any importance for related abyssal assimilation.

Thick magmatic bodies are stirred by ordinary thermal convection and also by the downstoping of blocks and by the later rise of secondary liquids developed by pure melting and solution of sunken xenoliths, as well as wall rocks, in depth. Here again the quantitative importance of process is not to be estimated by the use of field observations alone.

To summarize: If syntexis is volumetrically significant, it must be largely abyssal rather than high level; and, as far as the absorption of rocks derived from the roof is concerned, it is chiefly xenolithic and at depth. Incorporation of blocks above has its corollary: assimilation below. Syntexis of the rocks along main contacts should be at maximum at great depth, where the invaded formations are initially hot and the cooling of the liquid slow.

Examples of High-level Assimilation.—Although at high levels hybrid rocks have small volume, they mean much for the problem as a whole; we shall do well to review some of the outstanding instances where visible products of syntexis have been reported (see Table 37). According to the general theory each volume of rock originating through magmatic assimilation, visible or directly inferred at rock outcrops, represents but a small fraction of a small fraction of the volume of primary melt that was engaged in the solution. Although only a small fraction of a small fraction, the total volume of post-Archean rock differentiated from high-level hybrid magmas may be great in absolute measure. But the meaning of high-level phenomena attains its full dignity only when its results are correlated with the more difficult, much more significant problem of abyssal assimilation. If high-level assimilation is real and notable, then abyssal assimilation is real and *a fortiori* notable. The case is strictly analogous with that for pure melting of solid rock in erupted magma and in the substratum.

Examples of syntectic rocks will be discussed in Chapters XVII to XXII, but for present convenience these are also included in Table 37. The different cases are classified in five groups, according to the nature of the dissolved rocks. Some Pre-Cambrian examples are included.

The examples of the table represent very different—both relative and absolute—amounts of assimilation. As described, its effects range from the microscopic to those involving many cubic kilometers of secondary magma.

In general, the comparatively "dry," gas-poor magmas, here listed, dissolved rocks more siliceous than themselves. This rule matches Bowen's deductions regarding the role of latent heat and his reaction principle, though the cooperation of some superheat cannot be easily excluded.

TABLE 37.—REPORTED CASES OF ASSIMILATION

Group 1 Assimilation of quartz-rich igneous rocks

Region	Rock assimilated	Assimilating magma	Product (with or without latter differentiation)	Authority, with date
Adirondack Mountains..	Granite	Gabbro	Acid gabbro, diorite, etc.	Miller, 1913
Cinder Cone, California.	Dacite	Basalt	Quartz basalt	Finch and Anderson, 1930
Island of Mull	Granophyre	Gabbro	Quartz-bearing porphyry	Thomas, 1924
Island of Skye.	Granite	Basalt	Acidified basalt	Harker, 1904
Blekinge, Sweden ...	Gneiss	Olivine diabase	Micropegmatitic diabase	Moberg, 1890
Loftahammar, Sweden	Granite	Gabbro	Micropegmatite	Gavelin, 1910
Nordingrå, Sweden.... .	Granite	Diabase	Monzonite and micropegmatitic rocks (adamellite, banatite, quartz porphyry)	Sobral, 1913
Almunge, Sweden........	Granite	Umptekite	Nordmarkite, etc.	Quensel, 1914
Kola Peninsula........ .	Granite	Ijolite	Pyroxene syenite	Hackman, 1894
Rhodesia	Granite	Dolerite	Granophyre	Mennell, 1911
Natal	Granite	Dolerite	Micropegmatitic hybrid	Prior, 1910

Group 2. Assimilation of quartz-poor and quartz-free igneous rocks

Region	Rock assimilated	Assimilating magma	Product	Authority, with date
Essex County, Massachusetts.	Gabbro-diorite	Granite	Hybrids	Clapp, 1921
Onaping, Ontario... . .	Basic volcanics	Granite	Basic granite	Collins, 1917
Athapapuskow Lake, Manitoba.	Basic lavas	Granite	Quartz diorite and granodiorite	Wright, 1931; Bruce, 1918
Katmai and vicinity, Alaska.	Andesite	Rhyolite	Hybrids	C. N. Fenner, 1920, 1923
Carlingford, Ireland......	Gabbro	Granophyre	Hybrids	Sollas, 1894
Isle of Man	Greenstone	Alkali granite	Acid granodiorite	Nockolds, 1931
Arran, Scotland	Gabbro	Granite	Diorite, quartz diorite	Tyrrell, 1928
Arran, Scotland	Gabbro, basalt	Granophyre	Craignuritic types	Tyrrell, 1928
Island of Mull	Basalt	Felsite-granophyre	Hybrids (dioritic)	Bailey and Thomas, 1924
Island of Rum	Eucrite	Granite	Hybrids	Harker, 1909
Island of Skye	Gabbro	Granophyre	Marscoite	Harker, 1904
Island of Skye	Basalt	Gabbro	Gabbro	Harker, 1904
Mountsorrel district, England.	Quartz diorite	Granite	Hybrids	Lowe, 1926
Dartmoor, England	Basic igneous rocks; shales	Acid granite	Basified phases	Brammall and Harwood, 1932
Dolgelley, Wales....... .	Dolerite	Granophyre	Hybrids	Cox and Wells, 1927
Oslo, Norway	Augite porphyrite	Nephelite syenite pegmatite	More mafic nephelite syenite	Brögger, 1899

TABLE 37.—REPORTED CASES OF ASSIMILATION.—(*Continued*)

Group 2 Assimilation of quartz-poor and quartz-free igneous rocks —(*Continued*)

Region	Rock assimilated	Assimilating magma	Product	Authority, with date
Sierra Leone	Norite	Norite	Norite	Dixey, 1922
Madagascar	Gabbro	Nephelite syenite	Nephelite-bearing monzonite	Lacroix, 1922
Group 3. Assimilation of highly siliceous sediments				
Medford, Massachusetts .	Quartzite	Diabase	Micropegmatite	Jaggar, 1898
Sudbury, Ontario .	Quartzite	Norite	Micropegmatite	Coleman, 1907
Onaping, Ontario	Quartzite (and granite)	Diabase	Micropegmatite and quartz-feldspar rock	Collins, 1917
Algoma, Ontario .	Quartzite	Diabase	Acidified diabase	R. C. Emmons, 1927
Espanola, Ontario	Quartzite	Diabase	Micropegmatite	Quirke, 1917
Pigeon Point, Minnesota	Quartzite and argillite	Gabbro	Micropegmatitic "red rock"	Bayley, 1893; Lawson, 1893; Winchell, 1900 Daly, 1917
Little Saganaga Lake, Minnesota.	Siliceous sediments	Gabbro	Quartz gabbro	A. N. Winchell, 1900
Tintic, Utah .	Quartzite	Monzonite	Rhyolite	Loughlin, 1919
Washington State	Swauk sandstone	Basalt	Micropegmatite	A. Waters (personal communication)
Purcell Mountains, British Columbia and Idaho.	Quartzite	Gabbro	Micropegmatite	Daly, 1905; Calkins, 1909
Coast Range, Alaska . .	Siliceous schists and sediments	Quartz diorite and granodiorite	"Assimilated rock"	Buddington, 1927
Firth of Forth.	Quartzose rock	Diabase	Quartz diabase	Stecher, 1888
Kilsyth-Croy, Scotland . . .	Highly siliceous rock	Diabase and gabbro	Micropegmatitic diabase and gabbro	Tyrrell, 1909
Mull, Scotland . .	Quartz fragments	Basalt	Granophyre and diorite	Bailey, Wilson, Thomas, 1924
Mull, Scotland	Sandstone	Granophyre	Acid hybrid	Bailey, 1924
Lake Wettern, Sweden. . . .	Quartzite and sandstone	Diabase	Micrographic quartz diabase	Hedstrom, 1906; Hogbom, 1909
Oslo, Norway.	Sandstone	Nephelite syenite pegmatite	Granite pegmatite	Brogger, 1899
Portuguese East Africa. . .	Siliceous rocks	Dolerite syenite pegmatite	Micrographic acid rock	Teale, 1924
Bushveld, Transvaal	Quartzite and argillite	Norite (initially gabbro?)	Acidified norite, granophyric norite	Hall, du Toit, 1923; Wagner, 1924; Daly, 1928
Vredefort, Orange Free State	Quartzite (and granite)	Gabbro	Micropegmatite etc.	Hall and Molengraaff, 1925
Granitberg, Southwest Africa.	Quartz-rich sediments	Nephelite syenite	Granite, pulaskite, nordmarkite	Kaiser, 1926
Mt. Greenock, Victoria, Australia.	Quartz xenoliths	Basalt	Acidified basalt	C. Fenner, 1915
Odenwald, Germany.	Siliceous schists	Gabbro	Diorite	Klemm, 1906
Odenwald.	Siliceous schists	Hornblende granite	Biotite granite	Klemm, 1906

TABLE 37.—REPORTED CASES OF ASSIMILATION.—(*Continued*)

Group 4. Assimilation of argillaceous and other basic sediments and schists

Region	Rock assimilated	Assimilating magma	Product	Authority, with date
Adirondack Mountains ..	Basic sediments	Gabbro	Syenite	Miller, 1913
Haliburton-Bancroft, Ontario.	Amphibolite	Granite	Basic granite	Adams and Barlow, 1910
Minnesota	Argillite	Gabbro	Cordierite norite	A. N. Winchell, 1900
Elkhorn, Montana . .	Basic sediments	Andesite	Latite, syenite	Barrell, 1901
Island of Mull... . .	Argillaceous sediments	Tholeiite	Cordierite buchite	Thomas, 1922
Northeastern Scotland ...	Argillite	Gabbro	Cordierite norite, etc	Read, 1921
Inchcolm Island	Argillite and calcareous sandstone	Picrite	Teschenite	Campbell and Stenhouse, 1907
Isle of Man	Greenstone	Alkali granite	Acid granodiorite	Nockolds, 1931
Dartmoor, England	Shale	Granite	Hybrids	Brammall, 1931, 1932
Lake Jänisjarvi, Finland	Mica schist (originally argillaceous)	?	Dacite	Eskola, 1921
Fichtelgebrige	Phosphoritic slate	Granite	Apatite-rich granite	Berg, 1927
Pallet, France	Argillite	Gabbro	Cordierite norite	Lacroix, 1899
Madagascar . . .	Mica schist	Granite	Syenite rich in sillimanite and corundum	Lacroix, 1922
Ambon Island .	Cordierite gneiss	Dacite	Cordieritic dacite	Brouwer, 1925

Group 5. Assimilation of carbonates

Region	Rock assimilated	Assimilating magma	Product	Authority, with date
Bancroft, Ontario	Limestone	Granite	Calcite-bearing plutonics	Ellsworth, 1924
Gilpin County, Colorado .	Calcareous rock	Monzonite	Garnet-wollastonite-bearing monzonite	Bastin and Hill, 1911
Becket, Massachusetts	Limestone	Granite	Pyroxene gneiss (granite)	Eskola, 1922
Philipsburg, Montana .	Limestone	Aplite	Scapolitic pyroxene aplite	Calkins, 1913
Ice River, British Columbia	Limestone	Nephelite syenite	Calcite-bearing nephelite syenite	Allan, 1914
Alno, Sweden.	Limestone	Nephelite syenite	Calcite-bearing nephelite syenite	Högbom, 1892
Almunge, Sweden	Limestone	Nephelite syenite	Vesuvianite-bearing canadite	Quensel, 1913
Hortavaer, Sweden.	Limestone	Pyroxenite	Hortite (hybrid rock)	T. Vogt, 1915
Polzen.....	Limestone	Basalt	Polzenite, luhite	Scheumann, 1922
Moravia	Limestone		Titanite-rich rocks	Pacák, 1926
Riesengebirge......... ...	Limestone	Granite	Calcite granite	Brögger, 1921
Alibert, Siberia........ .	Limestone	Nephelite syenite	Graphitic rocks	Laitakari, 1925

TABLE 37.—REPORTED CASES OF ASSIMILATION.—(*Continued*)
Group 5 Assimilation of carbonates —(*Continued*)

Region	Rock assimilated	Assimilating magma	Product	Authority, with date
Sviatoy Noss, Transbaikalia	Limestone	Granite	Sviatonossite	Eskola, 1921
Madagascar	Limestone	Granite	Garnetiferous syenite with primary calcite	Lacroix, 1922
Granitberg, Southwest Africa.	Limestone	Nephelite syenite	Femic nephelite syenite	Kaiser, 1926
Marble Delta, Natal	Dolomite	Granite	Desilicated, pyroxene-bearing granite	Du Toit, 1920
Vredefort, Orange Free State	Limestone	Alkaline granite	Nephelite syenite	Hall and Molengraaff, 1923
Spitzkop, Transvaal	Limestone	Nephelite syenite	Ijolite	Shand, 1922
Merapi, Java	Limestone	Andesite	Phonolite and trachyte	Brouwer, 1928
Marulan, New South Wales	Limestone	Quartz monzonite	Diopside rock	Osborne, 1931

The cases of Group 2 seem to demand the assumption of superheat in the respective magmas, or else the assumption of special gas fluxing. The field evidence does not appear to compel choice between these hypotheses.

For Group 5 and for many systems of Groups 3 and 4, connate water and carbon dioxide were likely to have been powerful aids in the incorporating process; no magmatic superheat need be postulated.

The reader will note the large number of individual rock species described by the various writers as of secondary origin.

A General Objection.—Correct inference has long escaped some petrologists because they have failed to distinguish between absolute and relative values. Those authorities are essentially pure differentiationists because of their single-minded emphasis on an obvious fact: primary magma cannot dissolve cool country rock to the extent of more than a small percentage of its own weight. All must agree with that statement. But the general problem really involves two distinct questions. First, what is the actual, though small, proportion of foreign material that can be dissolved by primary magma? Second, what is the absolute volume of a magmatic body which is capable of such a degree of contamination? This second question particularly has been too much neglected, with results disastrous to rigorous thinking.

Volume Relation of Primary Magma and Assimilated Rock.—How can the shape and size of a magma chamber in depth, where alone syntexis on the large scale is possible, be visualized? This query has no useful answer apart from a theory of the earth's constitution and dynamic history. Since he cannot be sure of the correct theory, the

petrologist takes the next best step; he chooses the most probable theory as a foundation for his thought regarding the volumes of magma. The favored choice has been described in the foregoing chapters. Its postulates include the reality of a true crust, which rests upon a continuous, vitreous, Simatic substratum; the development of throughgoing shears in the crust, with consequent abyssal injection of molten basalt into the crust—processes especially at work during an orogenic crisis; the "bottomless" character of the largest abyssal injections, "bottomless" in the sense of passing down directly into the hot, vitreous, pressure-viscous substratum itself; and the necessity of major stoping and piecemeal stoping, these displacements of crust rocks being also chiefly confined to epochs and zones of mountain building.

The adopted theory of the earth implies great volumes for magmatic bodies intruded along orogenic belts. Within the belts injections of molten Sima have heights that are nearly or quite equal to the whole thickness of the crust, 60 or more kilometers. The widths of some of these injections, where they pass into the substratum, may be even greater than their heights, if major stoping is the principal cause of the injections. Thus abyssal injections are conceived to attain individual volumes that reach scores of thousands to perhaps a few millions of cubic kilometers.

If a large injection incorporates country rock to the extent of only 5 or 10 per cent of its own volume, the replacing and assimilative effects may still be very great by absolute measure.

Much more voluminous, secondary magma would be generated if, by major stoping, thick sections of the crust should founder bodily in the substratum. There, well below the bottom level of any abyssal injection, the great blocks would slowly but surely melt, and their assimilation, though partial, would also be on a large scale. With density lowered by the change of state, the secondary melt of either origin rises through the substratum into the mountain roots. For the moment we concentrate attention on the quantity of secondary magma thus formed by true assimilation. The latter will, of course, consist chiefly of the mixture of the primary basic material with that along the boundary of each melted block.

However and wherever developed, a hybrid magma implies heat sufficient for the mutual solution. We therefore turn to the second principal question: What thermal energy is available in abyssally injected magma for the assimilating process?

Magmatic Temperatures Observed.—Lavas at volcanic vents (reaching maximum temperatures of 1200° or somewhat more) do not give a trustworthy idea of the initial temperature of basalt which

has been injected into the earth's crust.[1] On the one hand, the lavas of a central vent have usually stood some time in their narrow vents, there losing heat by convection and radiation to the sky and by conduction to the surrounding rocks. On the other hand, as noted in Chapter XV, a central vent is probably a true furnace, where new supplies of heat are generated by chemical reactions within the lava at the vent itself. A valid opinion about the net effect of these contrasting processes on the temperature can at present hardly be reached.

Magmatic Temperatures Inferred.—Attempts have been made to deduce the temperatures of magmas from the thermal changes wrought on xenoliths. Sosman and Merwin give 1150° as the maximum possible temperature of the intrusive Palisades diabase, on the ground that inclosed blocks of feldspathic sandstone, which melt at that temperature, were not liquefied.[2] While this observation does give a limit of temperature when the inclosure took place, it does not necessarily indicate the highest magmatic temperature. Before the inclosure of the visible blocks, the magma may well have been hotter, even to the point of melting and assimilating other xenoliths of the sandstone

From the effect of dike basalt of Arran on xenoliths of pitchstone, Tyrrell deduces a magmatic temperature between 1170° and 1375°. Vogt believed the temperature of the Alnö magma, when it inclosed blocks of limestone, to have been "1300° or a little higher." Thomas concludes that the xenolith-bearing basic magma of Mull was at about 1400°; that the metamorphism of the xenoliths "was continued through a prolonged period of slow-cooling until about 1250°; and that, after this, rapid cooling intervened as a result of sill-intrusion of the magma." Dixey describes a case in Sierra Leone where older norite was considerably assimilated by younger norite magma, implying a notable degree of superheat for the latter. According to Iddings, the temperature of the Yellowstone rhyolite was locally high enough to cause the fusion of inclosed fragments of basalt. C. N. Fenner (personal communication, 1929) reports a similar discovery in the National Park. These observations are particularly noteworthy, in view of the relatively high melting temperature of basalt.[3]

[1] According to G. W. Tyrrell (Volcanoes, London, 1931, p. 135), H. Philipp found the temperature of Etna lava to reach 1300°.

[2] R. B. Sosman and H. E. Merwin, Jour. Washington Acad. Sciences, vol. 3, 1913, p. 389.

[3] G. W. Tyrrell, Geol. Mag., vol. 2, 1916, p. 193. J. H. L. Vogt, Videns.-Skrifter, I, mat.-naturv. Kl., 1915, No. 8, pp. 28, 32. H. H. Thomas, Mull memoir, Geol. Survey Scotland, 1924, p. 278; Quart. Jour. Geol. Soc. London,

In a number of well-known papers, Lane has declared his view that only by postulating considerable superheat in some magmas can we explain the variation of grain in the corresponding intrusive bodies.[1]

Yet, after a discussion of the "geological thermometer," Shand states: "There is an entire lack of evidence that any body of deep magma ever had a temperature higher than 1170°, or that it even approached that figure," though the top layer of surface magma may be heated up by gas reactions to 1300° or more.[2]

This contrast of opinion is due to the complexity of the problem, which has to remain largely speculative. It is, then, worth while to examine relevant deductions from the crust-substratum-injection theory.

Superheat and Syntexis.—According to the theory, basalt, erupted along the fissures to form the basaltic plateaus, was moved quickly from the levels of the substratum to the earth's surface. Presumably the concentration of gas, with the corresponding exothermic reactions, could not have had much importance for the temperature of the issuing lava. Nevertheless, these basalts are famously fluent, running scores of kilometers and thinning down to thicknesses of only a few meters, in spite of the rapid radiation of heat during the long journey under the air (Stefan's law: radiation varying as the fourth power of the absolute temperature), and notwithstanding the lowness of the slopes traversed. The initial fluency and, still more, the prolonged fluency seem inexplicable unless we assume some degree of superheat. To the writer, this conclusion appeared inevitable long before 1922, when he studied a new, telling illustration in the plateau basalts of Basutoland, especially well seen along the marvellous cliffs of Mont-aux-Sources. Those flows show no evidence of having been originally rich in gas and for that reason of such low viscosity.[3]

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vol. 78, 1922, p. 250. F. Dixey, *ibid.*, p. 320. J. P. Iddings, Mon. 32, U.S. Geol. Survey, part 2, 1899, pp. 430–433.

What is the meaning of A. A. Weymouth's (Amer. Jour. Science, vol. 16, 1928, p. 237) finding cristobalite developed in a granitic block, apparently by the heat of the inclosing basaltic magma?

[1] A. C. Lane, Bull. Geol. Soc. America, vol. 14, 1903, p. 369; Rep. Geol. Survey Michigan for 1903 (1905), p. 205; other references in Bull. 746, U.S. Geol. Survey. Certain complications, including the effect of gas concentration, are omitted from Lane's mathematical discussion. For this reason his evidence for much superheat of magmas is not convincing.

[2] S. J. Shand, Eruptive Rocks, London, 1927, p. 56.

[3] *Cf.* A. L. du Toit, The Geology of South Africa, Edinburgh, 1926, p. 237. Though the high mobility of the plateau basalts at eruption is a commonplace of geology, its explanation has been singularly neglected. L. L. Fermor (Rec. Geol. Survey India, vol. 58, 1925, p. 198) credits initial superheat for the flows of the Deccan and explains it by assuming derivation of the basalt from eclogite and also an exothermic character for this transformation.

Again, superheat probably characterized the magma of basalt, diabase, or gabbro that has been injected as widely extended but thin sills. With that condition fulfilled we see how those intrusive melts could travel tens or scores of kilometers through cold sediments.

The crust-substratum theory makes such superheat probable, by deduction. According to Bowen, a thick vitreous earth shell would not be supersaturated (undercooled).[1] Let us assume no supersaturation. Let us assume further a rise of 3° in the melting temperature of basalt per kilometer of descent, and 60 kilometers as the thickness of the crust. The temperature of the top of the substratum would then be about 1330°, representing 180° of superheat, if without other change, this material were transferred to the earth's surface. If the extrusive material, also rising rapidly, came from a still deeper level in the substratum, the superheat would be somewhat greater.

For a similar reason considerable superheat of more salic magma seems possible. Granite, for example, contrasts with basalt in having a larger change of volume at melting, smaller latent heat, and therefore probably greater elevation of the melting temperature by pressure (see page 64). If, then, pure melting developed granitic liquid at the depth of, say, 50 kilometers, it might possibly be superheated as much as 200° when brought up close to the earth's surface. Have we here part of the explanation for the "caustic," replacing effect of many batholiths at visible contacts?

A second possible cause of superheat merits attention. The substratum has high viscosity. Injection of its substance into the crust must be accompanied by much internal friction and the development of new heat in the transferred material. This is the "isenkaumic" heating of Adams, the Joule-Thomson effect.[2] Its evaluation is difficult.

A third source of heat has been speculatively found in chemical reactions among the constituents of magma after this has been brought to levels of relatively low pressure. Such reactions are conceivable among the nonvolatile constituents as well as among the magmatic gases (see page 376).

A fourth cause of moderate superheat in erupted Sima is imaginable. If the temperature of the substratum increases downward, and if part of a major injection of basalt comes from a somewhat deep level in the

[1] N. L. Bowen, Jour. Geol., vol. 27, 1919, p. 400. C. H. Desch (Trans. Faraday Soc., vol. 20, 1925, pp. 472, 480) and A. Scott (*ibid.*, p. 498) prefer to believe that undercooling of magmas in depth is quite possible, if not probable.

[2] L. H. Adams, Jour. Washington Acad. Sciences, vol. 12, 1922, p. 407; Jour. Geol., vol. 32, 1924, p. 191; Jour. Indust. and Eng. Chem., vol. 15, 1923, p. 610.

substratum, that part brings with it a corresponding excess of temperature.

Probably the actual superheat of a large abyssal injection has seldom exceeded 200°. Yet even this amount alone would mean excess thermal energy, available before saturation sets in and equal to about 70 calories per gram; for at the high initial temperature the specific heat of the melt would be close to 0.35. The excess energy of the stated amount would be one-seventh of the total melting heat of basalt. The ratio of superheat to melting heat for salic magma which had originated by pure melting at great depth would be still larger.[1]

Latent Heat and Assimilation.—The crust-substratum-injection hypothesis thus implies a limited amount of superheat in basalt immediately after its rise from the substratum levels. Less speculative and clearly significant for the present problem is the latent heat. This is at least one-fifth of the total melting heat of the basalt, and it must be got rid of during crystallization. The process has two results: the country rocks are heated by conduction; and some of them, especially those more siliceous than basalt, are dissolved by the primary melt. Bowen has made much clearer just how the latent heat is made available for the true solution of solid rocks. He is of opinion that nearly all actual syntexis is to be so explained, that is, by "reactive solution," as he well phrases this important principle.[2]

Limit of Assimilation.—Let us assume, then, that a body of basaltic magma, reaching from the substratum nearly to the earth's surface, can dissolve foreign rock to the extent of 10 per cent of its own weight. What does this ratio mean with respect to the *absolute* amount of rock absorbed? Suppose the height of the basaltic invader of the crust to be 60 kilometers. Ten per cent of 60 kilometers represents a vertical thickness of rock greater than the visible thickness of any known batholithic mass. If the major basaltic injection flares strongly in a downward direction, the vertical thickness of the (gravitatively

[1] That such deductions may be guiding on the right track seems indicated by C. N. Fenner's able study of Katmai, one of the few volcanoes investigated by a trained physical chemist who is also a geologist (Jour. Geol., vol. 28, 1920, p. 594). After detailing evidence of remarkable assimilation of basic rocks by the salic magma of the region, Fenner concludes that this magma was somewhat superheated, though supplementary thermal energy may have been added by rising gases. In the face of his determinations at Katmai, Fenner (Miner. Mag., vol. 22, 1931, p. 542) writes: "I cannot believe that rhyolites represent simply the last remaining and coldest liquid derived from the crystallization of basalt. Some large source of energy is required which is not provided in the theory."

[2] N. L. Bowen, Jour. Geol., vol. 30, 1922, p. 541; The Evolution of the Igneous Rocks, Princeton, 1928, p. 175. Bowen's refusal to attribute any essential significance to superheat in pure melting and assimilation is not based upon good evidence.

differentiated) product of its syntexis with Sialic rock could be still greater than 6 kilometers. Thus incorporation of hundreds of cubic kilometers of Sialic rock in a single basaltic injection seems theoretically possible.

The foregoing estimate is intended to illustrate the heat problem on its quantitative side. The statement of the assumptions thus made should not be taken to portray the actual conditions for the development of batholiths. A very different explanation of the greater intrusions, founded in part upon the idea of major stoping, has already been noted and will be more fully described in a later section of this chapter.

Assimilation of Connate Fluids.—Multitudes of xenoliths, originally rich in water, carbon dioxide, and other volatile connate fluids, have resisted bodily absorption by their containing magmas and yet have lost nearly all of these fluids. Thus blocks of argillaceous sediments, when containing 5 to 10 per cent water by weight, have been inclosed by magma and converted into hornfelses and other metamorphic rocks which now have much lower contents of water. Where xenoliths of limestone and dolomite are changed to masses of lime silicates, about 40 per cent of the original sediment disappears. Such vanished volatiles have obviously been dissolved in the host magmas.[1]

With scarcely less certainty, water, carbon dioxide, chlorine, and sulphur have been driven into the magmas from belts of contact metamorphism around intrusive bodies. The Transvaal supplies an illustration of real grandeur. The Pretoria shales and sandstones beneath the Bushveld norite were converted to contact fels down to a maximum stratigraphic depth of about 2500 meters. According to the minerals now present, the volatile matter in the contact fels is seen to be of small amount. An abundant phase rich in cordierite shows a loss on ignition of only 1.3 per cent, and two xenoliths of the shale, no more metamorphosed than the shale beneath the norite, have, respectively, 3.20 and 2.40 per cent of total volatiles.[2] Unfortunately no representative analyses of the unaltered Pretoria shales have been made, but Horwood gives one for the still older shale of the Hospital Hill series. This afforded 5 per cent water, a quantity practically identical with the percentage in Clarke's composite analysis of seventy-eight shales.[3] Since the Pretoria shales were deposited just before the

[1] Fine illustrations on a large scale are described by H von Eckermann at Tennberg, Sweden (Medd. Stockholms Högskola, Mineralog. Inst., No. 43, 1923, p. 480, and plates 14 and 15).

[2] See A. L. Hall, Trans. Geol. Soc. South Africa, vol. 11, 1908, p. 10; vol. 14, 1911, p. 74.

[3] C. B. Horwood, Trans. Geol. Soc. South Africa, vol. 13, 1910, p. 29. F. W. Clarke, Bull. 695, U.S. Geol. Survey, 1920, p. 29.

Bushveld norite was erupted, their average content of volatiles was probably greater than 5 per cent. Hence a huge volume of sediments beneath the norite have lost several per cent—perhaps considerably more than 3 per cent—of volatile matter by weight. The volatilized material must have gone principally into the norite, and some of it during the liquid stage of the eruptive.

Again, when geosynclinal sediments are thrust down or otherwise sunk into a major magmatic wedge or into the substratum itself, such "anti-pneumatolysis" must take place. The absorbed gases diffuse upward and at the higher levels increase the fluidity and solvent power of the absorbing material. Thus both magmatic differentiation and assimilation of solid rock are somewhat favored.[1]

Many petrologists doubt any important absorption of gases by magmas at main contacts. One argument is that, because pegmatitic and allied solutions are effluent from their parent bodies, the movement of the gases freed at main contacts is similarly effluent or centrifugal.[2] Anyone who has seen a high-powered well of natural gas blow off obtains a lively sense of the highly impervious character of even sedimentary rock. The country rocks of many igneous intrusions must be at least as impervious to the flow of gas as those sediments that have held in hydrocarbons at high pressure for millions of years. The heat of each large intrusion develops great gaseous pressure in country rocks with abundant volatile matter. It seems inevitable that the back pressure should, under no uncommon circumstances, drive these foreign, "resurgent" gases into the magma. Allen, Morey, and their colleagues at the Geophysical Laboratory of Washington have shown how water of the walls, under the back pressure described above or even under purely hydrostatic pressure, must be dissolved by the adjacent magma.[3] There is no theoretical reason why the incorpora-

[1] Compare the views of A. L. Day and E. T. Allen as to the importance of the solution of foreign water in undercooled magma (Pub. 360, Carnegie Inst. of Washington, 1925, p. 83). T. Barth (Norsk geol. Tidsskrift, vol. 9, 1926, p. 301), following a suggestion of V. M. Goldschmidt, holds that magma may absorb from country rock carbon dioxide previously released from its compounds during regional metamorphism. By the assimilation of carbon dioxide Goldschmidt explains the primary calcite in hortite.

[2] Thus F. F. Grout (Bull. Geol. Soc. America, vol. 39, 1928, p. 567) writes: "The well-known fact that many magmas give off hydrous emanations makes it seem unlikely that a wall rock which receives water from a magma should contribute water to the magma." Yet clearly emanation at the late stage of crystallization does not preclude absorption of foreign water at an earlier stage.

[3] E. T. Allen, Jour. Franklin Inst., vol. 193, 1922, p. 32. G. W. Morey, Jour. Washington Acad. Sciences, vol. 12, 1922, p. 228, and Jour. Geol., vol. 32, 1924, p. 292. A. L. Day, Jour. Franklin Inst., vol. 194, 1922, p. 578, and vol. 195, 1924, sep. p. 15. *Cf.* P. Niggli, Die Naturwissenschaften, vol. 44, 1916, p. 667;

tion of foreign volatiles need stop at the point where they saturate the magma; no antecedent reason why the entering gases may not be in excess and form bubbles.

A simple illustration of such resurgence is found in the formation of "fumaroles without roots," so named by Lacroix and later discussed by Allen. The water in the ground beneath a lava flow is vaporized by the heat. The steam rises through the lava, mingles with its juvenile gases, and generates the secondary fumaroles.[1] The commonly accepted explanation of pipe amygdules at the bottoms of basaltic flows also implies the addition of foreign water to primary magma.[2]

Again, the refusal to recognize resurgence as an important control in petrogenesis and minerogenesis has been largely due to too much emphasis upon pure differentiation in the theory of igneous rocks. Of late, opinion has swung to a more reasonable position, and the necessity of assuming some magmatic assimilation—if not the pure melting—of crust rocks is causing geologists of increasing number to accept a secondary origin for some of the volatile matter in natural melts.

The economic geologists have been slow to admit the idea, though obviously of moment in their problems. However, even this group is beginning to shift ground. While Lindgren, for example, makes "magmatic fluid" and "juvenile fluid" synonymous according to the main text of his "Mineral Deposits," he does admit that a "small part" of the volatile matter in a magma may have been absorbed from the country rock.[3] Much better balanced in this respect is Berg's

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F. A. Perret, Pub. 339, Carnegie Inst. of Washington, 1924, p. 80. J. P. Iddings (The Problems of Volcanic Action, New Haven, 1914, p. 249) wrote: "The contact of molten magmas with limestones and other rocks bearing carbonates leads to . . . the liberation of large volumes of carbon dioxide, which must escape in part into the liquid magma." On page 252 of the same volume Iddings noted that foreign water must be similarly absorbed by magma.

Is there any better explanation of the white-trap phases of the Scottish sills and dikes than that founded on the assumption of the volatilization of carbonaceous matter from the intruded shales, with consequent reduction of the iron oxides in the original basaltic material? See Sir J. Flett, Summary of Prog., Geol. Survey Great Britain for 1929, part III, p. 64.

[1] A. Lacroix, La Montagne Pelée et ses Eruptions, Paris, 1904, p. 390; *cf.* E. V. Shannon, Jour. Geol., vol. 27, 1919, p. 579. E. T. Allen, Jour. Franklin Inst., vol. 193, 1922, p. 36. See also C. N. Fenner, Annals New York Acad. Sciences, vol. 20, No. 2, 1910, p. 104.

[2] T. L. Walker and A. L. Parsons, (Univ. Toronto Geol. Studies, No. 16, 1923, p. 9) describe pipe amygdules, 6 inches in diameter and extending from base to top of a basaltic flow in Nova Scotia. The gas that made them was steam generated at the floor of the flow and was most graphically resurgent. For another example see J. A. Bartrum (Bull. 12, Auckland Univ. Coll., 1930, p. 451).

[3] W. Lindgren, Mineral Deposits, New York, 3d ed., 1928, pp. 34, 93.

treatment of magmatic volatiles, since he repeatedly stresses the resurgent class.[1]

Many other able authorities have adopted the principle of resurgence. Among them the names of Erdmannsdörffer, Kaiser, Niggli, Oulianoff, Pacák, Scheumann, and Shannon may be mentioned.[2]

If the names of the writers who have recently discussed the origin of the alkali-rich rocks (see especially Chapter XXI) were added, this list would be considerably extended.[3]

According to Goldschmidt, resurgence on a big scale may be assumed to account for the rock "stems" represented in folded mountains through lengths of "thousands of kilometers"; the connate water of the corresponding geosynclinal prisms is thought by Goldschmidt to have been incorporated by primary magma, with the resulting differentiation of these particular stems. Vogt approved of the hypothesis in principle.[4]

Classification of Magmatic Gases.—We conclude that magmatic volatiles have diverse origins. Table 38, suggesting a genetic classification for them, is interpolated because of some convenience in the later discussion of differentiation and of volcanic action. The table

[1] G. Berg in Chemische Geologie, by F. Behrend and G. Berg, Stuttgart, 1927, pp. 24–27, 171, 195, 198, 205.

[2] O. H. Erdmannsdörffer, Grundlagen der Petrographie, Stuttgart, 1924, p. 161. E. Kaiser, Sitzungsber. Bayer. Akad. Wiss, math.-phys. Kl., 1922, p. 267; Die Diamantenwüste Südwest-Afrikas, Berlin, 1926, vol. 1, p. 253. P. Niggli, Die Naturwissenschaften, vol. 44, 1916, p. 667; Die Leichtflussigen Bestandteile im Magma, Leipzig, 1920, pp. 123, 202. N. Oulianoff, Bull. soc. Vaudoise sci. nat., vol. 55, 1922, sep. p. 15. O. Pacák, Bull. internat Acad. Sci. Bohême, 1926, p. 87. K. H. Scheumann, Centralbl. f. Mineralogie, etc., 1922, p. 527. E. V. Shannon, Jour. Geol., vol. 27, 1919, p. 579; Proc. U.S. Nat. Museum, vol. 66, 1924, art. 2, p. 37.

The diabase sills studied by Shannon and prompting his conclusion are analogous with the Pigeon Point sill, where Grout thinks not "much" water was absorbed by the basic magma. It would aid discussion if a definition of "much" were given.

[3] J. Gilluly (Amer. Jour. Science, vol. 14, 1927, p. 199) gives an account of Utah injections of analcite diabase with late differentiates of analcite syenite. The diabasic magma was intruded into sediments, but before its arrival it is supposed to have been decidedly richer in water than ordinary diabasic or basaltic magma. The question as to the origin of the excess water is not touched by Gilluly.

[4] V. M. Goldschmidt, Videns.-Skrifter, Oslo, Kl. I, 1922, No. 10, p. 7. J. H. L. Vogt, *ibid.*, 1924, No. 15, p. 89. In striking contrast C. S. Ross (Econ. Geol., vol. 23, 1928, pp. 869, 877), while admitting the probability of resurgence for "materials redissolved" from country rocks, does not, in a general study of magmatic volatiles, consider the solution of connate water from the same rocks as worthy of mention.

covers also phreatic gases and vapors, since these are likewise associated with volcanism.

Phreatic gases and vapors are of atmospheric or oceanic origin and include both volatilized *seepage* waters and volatilized *connate* waters, those trapped in sediments and other solid rocks at the time of their formation.[1]

TABLE 38.—VOLATILE AGENTS ENGAGED IN IGNEOUS ACTION

Magmatic volatiles (volcanic; internal)	Juvenile	Direct emanations from abyssal injection
		Emanations from primary solid country rock
	Resurgent	Connate and seepage volatiles absorbed by magma during syntexis (pure melting, assimilation, or both) of country rock
		Connate and seepage volatiles absorbed by magma independently of syntexis of solid rock
Phreatic volatiles (subvolcanic; external)	Seepage	
	Connate: (1) in place, (2) distilled and migrating	

ORIGIN OF SOME SUBJACENT BODIES. ABYSSOLITHS

An earlier speculation regarding the origin of many so-called batholiths and stocks was founded upon the classic contraction theory of mountain ranges. Thereby the author accounted for the visible rocks of the subjacent bodies: as gravitative, felsic, differentiated cappings of specially wide abyssal injections of basalt. These great intrusions of basic magma were supposed to have assimilated or melted up parts of the Sial, with accompanying and following gravitative differentiation of the less dense salic magma. The energy required to do the work of incorporation was found chiefly in the heat of the primary injections. It logically followed that the differentiated salic magma of each of these truly bottomless intrusions was but a small part of the whole, and that the major part was basaltic, self-cleansed, primary material. Magmatic stoping was thought to have enlarged each great chamber, but only to a limited extent, increasing the height perhaps 10 to 15 per cent. Stoping and assimilation could thus account for the space occupied merely by the upper part of each batholithic mass.

That older explanation of subjacent bodies became subject to doubt as evidence accumulated that the level of no strain within the contracting earth is probably at a depth measurable not in kilometers but in tens of kilometers. A second difficulty was early felt when trying to account for the great widths of the abyssal injections,

[1] For a more detailed account of the classification, see R. A. Daly, Econ. Geol., vol. 12, 1917, p. 487. The technical use of "resurgent" was first proposed in the American Journal of Science, vol. 26, 1908, p. 48.

corresponding by hypothesis to the broad outcrops of some batholiths. The abyssal injections were supposed to have been so widened by the sudden release of horizontal tension at master fissures in the thick shell of tension, with rapid horizontal recoil of the rock composing this shell. Could so much tensional stress be borne by the earth's crust?

Multiplying proofs of low-angle thrusting, with amplitudes apparently too great to have been produced by the purely elastic potential of the crust, added a third difficulty. Then came the shocking conception of extensive horizontal displacements of crust blocks of continental dimensions. This could not fail to affect thought about the mode of major invasion of the crust by magma. Quite apart from the merits of Wegener's theory, it now seems probable that during each principal orogenic process big blocks of the Sial moved horizontally against neighboring parts of the Sial or against the suboceanic crust. Such displacements, with amplitudes of at least some tens of kilometers, were possible only through oblique shearing of the whole crust and consequent rise of substratum magma into the crust. This type of abyssal injection under mountain roots would be of unsymmetrical cross section. The intruded mass would be wide and theoretically might be at least as wide as the largest known batholith.

Further, the new idea of mountain building implied the necessity of strong downthrusting of the crust on the "prow" side of the moving block, if this moved far enough to develop a mountain structure. Major stoping of the crust along the zone of mountain building cannot be demonstrated as an inevitable accompaniment, but it is probable enough to furnish an important element in the problem of subjacent intrusions.

Let it be assumed that pure melting (with some marginal assimilation) of the downthrust and foundered Sial takes place within the substratum on the scale now visualized. The new, syntectic, salic melts would be expected to displace gravitatively the denser material of the primary Simatic injection and to perform some piecemeal stoping on the mountain roots above. Thus large volumes of salic magma as such would invade the mountain-built structure and bring with them from great depth thermal energy sufficient for batholithic activities. With major stoping dominant at first and piecemeal stoping at the last, the crosscutting and replacing nature of the typical batholith or stock becomes understood. Similarly with the other characteristics of subjacent bodies: their sizes and ground plans, their general restriction to, and elongation in, orogenic belts, the tendency of each to appear specially along one side of the orogenic belt, the final emplacement after the orogenic paroxysm, the details of roof and walls (pendants, cupolas, shatter zones, etc.), the intimate

relation to regional metamorphism, the downward enlargement at visible outcrops, the salic composition, and the prevailing order of plutonic eruption, from basic to acid.

Further, the regular absence of strong positive anomalies of gravity at batholithic surfaces and the considerable altitude of these surfaces in regions of practically perfect isostasy are accounted for on this hypothesis better than by the author's former conception of batholithic origin.

Thus a body which has the size and structural relations of many a typical batholith is now pictured as beginning with the pure injection of the crust by magma, on a scale yet larger than that postulated in the 1914 version of orogenic theory.

The newer conception of mountain building also implies the probability of some enlargement (mechanical heightening) of a batholithic chamber by a delayed phase of the pure injection. The salic magma, with a density of about 2.4 as against about 2.7 for the surrounding rocks and with a vertical dimension of many kilometers, could not fail, through isostatic adjustment, to dome its roof somewhat. We have seen, in fact, that Lindgren and also Cloos believe there is field evidence of such doming of the roofs of bulky granites; Barrell thought it to be a common phenomenon. Perhaps the dome of the Island of Arran was at least accentuated by the process described.[1]

This effect of differential density in crustal readjustments need not be conspicuous at cupola exposures of subjacent bodies, for the country rocks alongside each cupola may themselves have risen with the doming of the whole roof over the mass of which the cupola is but an offshoot.

Attempts are being made to discern the essential mode of emplacement of great granite masses by studying detailed features—fluidal structures and joint systems (indications of tensions developed after freezing). The success of this method is questionable. The features selected for emphasis originated at a late stage in the history of each magma. The cooling of each took millions of years. Contraction of each mass by 10 per cent of its volume was inevitable. Just as inevitable were considerable readjustments of roof, walls, and intrusive

[1] See Plate 3 in G. W. Tyrrell's memoir on Arran (Geol. Survey Scotland, 1928), also the map of the island reproduced by E. B. Bailey (Geol. Mag., vol. 63, 1926, p. 485).

According to S. Paige (Folio 219, U.S. Geol. Survey, 1925), and R. Balk (Jour. Geol., vol. 39, 1931, p. 736) the Harney granite of the Black Hills, South Dakota, strongly domed its roof during its intrusion and in the process developed an excellent example of peripheral schistosity and centripetal dips. However, neither of these writers discusses the fundamental questions as to the origin of the granitic liquid and as to the depth at which it began the process of doming.

itself. These differential movements could not fail here and there to produce more or less conspicuous flow structures, stereotyped by final freezing. Other shears in the cooling body would not be unexpected if there had been hydrostatic doming or fracturing of the roof. Such late readjustments of the rocks under the prolonged stresses are natural developments *after* the intrusion of the granite has been almost entirely completed. They may tell us little or nothing about the real question at issue: How did each granite win the greater part of the space it occupies?[1]

A similar objection may be made to the use of joint systems of the granitic body. Representing still later adjustments of mass, their mapping seems even more unlikely to give results demonstrating the essential mechanics of intrusion. The irrelevance is evident where, as so commonly, the systems of master joints run through granite and country rock alike.

For a second reason the effort to deduce the mode of intrusion from the attitudes of flow lines and joints meets grave difficulty. Although most of the deformation of the country rocks took place before a typical batholith rose to observed levels, one need not assume complete release of horizontal orogenic pressure before the magma solidified. It would indeed be surprising if such were always the case. A moderate orogenic pressure, continuing through the cooling stage, might well leave some visible traces of shears and tensions—stereotyped flow structures and certain kinds of jointing. Moreover, there is no antecedent reason why the top of a batholith should not be so sheared away horizontally as to be more or less completely separated from the main salic chamber.

These considerations have weight in the discussion of the granitic massifs of Silesia and the adjacent part of eastern Germany. After careful mapping of flow structures and joints characterizing those bodies, Cloos and his school have become satisfied that the bodies were emplaced by pure injection and were forced into wedge shapes or mushroom shapes under mountain-building stress. Except at the comparatively narrow feeding channels, each body of magma had a solid floor.[2]

[1] J. Barrell (Amer. Jour. Science, vol. 1, 1921, p. 261) held that fluidal and protoclastic structures in the more felsic masses are "clearly features of decadence in magmatic invasion."

[2] H. Cloos, Das Batholithenproblem, Berlin, 1923; Der Mechanismus tiefvulkanischer Vorgänge, Braunschweig, 1921; Der Gebirgsbau Schlesiens, Berlin, 1922. Many other memoirs by Cloos and his associates are listed in a bibliography compiled by R. Balk (Bull. Geol. Soc. America, vol. 36, 1925, p. 695). It should be noted that Cloos has changed opinion somewhat, now more than formerly laying emphasis on the doming of their roofs by batholithic magmas (Einführung in die tektonische Behandlung magmatischer Erscheiningen, Berlin, 1925, p. 4).

These granites are located in the Variscian (Hercynian) mountain structure. The Variscian orogeny was prolonged. Its maximum occurred during the Sudetic (early Pennsylvanian) epoch, but it was continued into the Asturian (mid-Pennsylvanian) epoch. In view of the slowness of the magmatic cooling, a salic mass of indefinite depth and intruded to high levels in the crust, just after the main folding, might well have been sheared and pushed about during the later feebler deformation of the crust. Cloos himself appreciates the possibility of actual orogenic beheading of the magmatic column from which the visible granitic massifs were derived.[1] Thus the genetic problem is, in this part of Europe, complicated to a degree not evident in other mountain chains where crustal deformation during petrogenetic cycles seems not to have been so prolonged.

In any case, proof of pure injection and of harpolithic form for the granites of Central Europe would not necessarily indicate the shape, size, downward extension, or structural relations of the bodies from which these injected wedges were derived. The fundamental question remains as to how each magma made the greater part of its upward journey, from the deep levels where alone the temperature permits magma to form at all—a journey through vertical distances of tens of kilometers. To assume that the fluidal and allied textures and structures, which were clearly formed at the very close of the magmatic life, or even in the hot plastic state after complete crystallization, can directly show the essential method of the magmatic rise and intrusion is to make a quite unwarranted extrapolation from observed facts. Above all, this criterion is inadequate to prove that batholithic intrusion to visible levels has been regularly synchronous with the main foldings at the respective mountain ranges. As we have seen (page 120), the intrusion to these levels was characteristically later than the principal respective foldings. On the other hand, the initial magmatic invasion, of volume not much inferior to that of each completed eruptive mass, is here considered to have accompanied the folding. The additional rise of the magma, that is, the vertical enlargement of the magmatic chamber through the last few hundreds

[1] H. Cloos, Das Batholithenproblem, Berlin, 1923, pp. 22, 32, 34, 41. This author (Der Erongo, Berlin, 1919, p. 164) admits that the granite masses of Central Europe were erupted not earlier than the closing stage of the Variscian folding. It is significant that he (Neues Jahrb. f. Mineralogie, etc., B.B. 68 (B), Heft 1, 1931, p. 55) confesses to a "great and complete disappointment" when in 1929 he found the large granitic massifs of Brandberg, Erongo, and the Spitzkops in Southwest Africa to lack *Granittektonik*, that is, the structural evidence of having been emplaced according to the method that Cloos and his school have advocated for granitic massifs. There is a similar lack of systematized fluidal structures in many of the Tertiary stocks and batholiths of the North American Cordillera.

or thousands of meters, seems best explained by piecemeal stoping, well after the folding had reached its climax.[1]

While, therefore, some felsic bodies named "batholiths" in the literature have been shown to have solid floors and to be true injections analogous to phacoliths or chonoliths, many essential facts known about other intrusive massifs can be best correlated if we assume these, when liquid, to have passed directly into the vitreous substratum. Such masses would be bottomless in the sense of lacking floors of crystalline rock. They may be briefly referred to as *abyssoliths* (Greek *abyssos*, bottomless). The intrusives thus visualized in theory would literally be included among the subjacent bodies. Thus "abyssolith" represents a speculative conception and should not be taken as synonymous with "batholith," if the latter term is to retain the useful objective definition here advocated—a definition that leaves open the questions of floor and mode of emplacement.[2]

Basaltic, diabasic, and gabbroic dikes, emplaced by legato injection (emanating directly from the substratum) are similarly bottomless, according to the theory. They may be distinguished as *minor* or dominantly basaltic abyssoliths, the much larger, more irregularly shaped felsic masses being *major* abyssoliths.

Both kinds are conceived as essentially abyssal injections of magma from beneath the earth's crust. Both mean *displacement* of crust rock as the principal mode of intrusion. In the case of the major abyssoliths, however, that process has commonly been supplemented by piecemeal stoping or *replacement* of roof and wall rocks. To the observer at the erosion surface, the evidence of replacement may be impressive; yet, according to the author's present theory as well as its predecessor, the replacement phase of the intrusion by piecemeal stoping is much less important than the earlier phase, initial *injection* of the crust.[3]

[1] *Cf.* F. E. Suess, Geol. Rundschau, vol. 18, 1927, p. 153.

[2] According to the suggested definition, batholiths include (1) major abyssoliths, emplaced primarily by abyssal injection of the crust, (2) any large bottomless Archean bodies shown to have originated by anatexis in place (older rock fluxed by rising gas or otherwise—the process favored by the elder Suess even for post-Cambrian subjacent masses), and (3) extensive crosscutting intrusions until these can be proved to be true injections, having floors of older rock. Concerning the reality of class (2) we have recent discussions by E. S. Moore (Trans. Roy. Soc. Canada, *iv*, 1931, p. 21) and A. M. Macgregor (Geol. Mag., vol. 69, 1932, p. 18).

[3] The reader will note the continued stress on the close analogy between basaltic dikes and the most voluminous of all intrusions. Some geologists look with dismay at such an attempt to picture the essential mechanism of igneous action, regarding the extrapolation of the dike idea into the depths as indefensively speculative.

Summary

Secondary magmas are developed by gas fluxing, pure melting, and liquid assimilation of crust rocks. During early Pre-Cambrian time all three processes seem to have operated on a large scale. For the subsequent eras, gas fluxing has been important as a cause for continued action at volcanoes of the central type but throughout has doubtless been subordinate to the two other processes. Both of these are to be treated necessarily in a speculative way; conclusions as to their quantitative value in petrogenesis are sure to be long debated.

Since "Igneous Rocks and Their Origin" was published, the author has come to appreciate more clearly the possibility of pure melting as essential in the formation of post-Archean magmas, especially magmas of batholithic proportions. This idea has been suggested by the growing evidence for notable horizontal displacements of the Sial when mountain chains are constructed—individual displacements of at least some tens or scores of kilometers. Major displacements of the kind imply subsidence of the Sial along the belts of deformation. Speculatively, the subsidence takes two forms. Under the mountains the crust is thickened, with the development of deep Sialic roots. Second, the thorough fracturing of the crust is assumed to cause major stoping: the engulfment of large blocks of the Sial in the substratum itself, an earth shell which has an average temperature well above the melting temperature of the Sial. Both deep root and giant xenolith are subject to pure melting, the material of each thus yielding secondary salic magma. Rising through the denser Simatic melt, whether of the substratum in place or of "bottomless" injections within the crust, the new salic magma invades the roots of the mountain chain.

More familiar in petrological theory is the idea of magmatic assimilation. The marked difference of opinion on this subject is explained partly by the contrasted field experience of those who have discussed it, and partly by the varying emphasis of the writers on the petrogenetic conditions to be expected at great depth, far below the level of any visible igneous contact.

Some petrologists show a curious unwillingness to assume important assimilation, although this process means merely the addition of materials of the same kind as those already in primary magma, and although magmatic differentiation is a reversible reaction to temperature-pressure conditions. The scepticism of these authorities is

However, the same critics do not hesitate to extrapolate the "laccolith" idea or he "chonolith" idea into the depths. Is there really any smaller degree of peculation in their line of thought?

based upon theoretical assumptions regarding available supplies of heat and the correlated volumes of primary magma which could be involved. There is some field evidence for superheat in certain magmas, especially basaltic magma, but even here superheat is but moderate. Like the latent heat of primary magma, it can permit of assimilation only to a limited extent. Nor can the results of this process be very greatly increased by the presence of connate water and gases in the assimilated rock. Probably little more than 10 per cent of the volume of a basaltic injection represents the volume of foreign rock assimilable by the magma of that injection, conditions of post-Archean time being assumed. Many illustrations of high-level syntexis are given in the literature of petrology. These have value for two reasons.

First, because the assimilating process is necessarily much limited by the low temperatures of the high levels, its visible results suggest a much greater relative amount of intracrustal assimilation deeper down. The absolute size of the secondary magma so produced may well rival the visible volume of any known batholith.

Again, proved high-level syntexis, comparatively slight as it is, gives point to a still more weighty question: Should we not call upon the heat of the substratum in place, the great interior of the planet itself, to account for the more voluminous invasions of the crust by salic magmas? Bulky as these may be, their liquefaction would demand but a minute percentage of the heat in the substratum, which itself would in the course of time regain practically its original temperature by conduction from the deep interior. Accordingly, many subjacent masses are here explained as major abyssoliths, that is, gigantic injections of dominantly Sialic material, melted at levels quite below the earth's crust.

Naive reasoning from direct observations at the surface of erosion has led many petrologists to reject both of these explanations of the bulkier intrusives. A leading purpose of this chapter has been to emphasize once more that we are dealing with a three-dimensional planet, an earth so hot and so constituted as to compel the pure melting and assimilation of rocks to an extent manifestly impossible at the levels of actual outcrops.

CHAPTER XIV

MAGMATIC DIFFERENTIATION

Definitions. Scope of Chapter

Petrologists are not of one mind when defining the technical terms "differentiation" and "magmatic differentiation." Harker, Iddings, Tyrrell, Vogt, Niggli, Beger, and others regard the two expressions as synonymous and meaning the formation of differences in an originally homogeneous melt, whether through pure molecular diffusion in the liquid itself or through fractional crystallization or through any other separating process. For Iddings, differentiation was "the separation or splitting up of a homogeneous rock magma into chemically unlike portions." According to Tyrrell: "Differentiation may be defined as the process whereby a magma, originally homogeneous, splits up into contrasted parts, which may form separate bodies of rock, or may remain within the boundaries of a single unitary mass."[1]

German writers have usually followed another tradition. Erdmannsdörffer gives *Magmenscheidung* as a synonym for *molekuläre Differentiation* and hence to be distinguished from *Kristallisationsdifferentiation*. Von Wolff expressly separates *magmatische Differentiation* from *Kristallisationsdifferentiation*, and both from *Konvektionsdifferentiation*. Osann recognized the first two kinds only. On the other hand, Milch in his general review of the subject did not so restrict "magmatic differentiation."[2]

Following the more widely extended usage, "differentiation" with synonym "magmatic differentiation" will here mean the separation or aggregation of fractional amounts of a magma, homogeneous or not, so that at least one submagma, chemically contrasted with the parent magma, is produced; crystal fractionation is included.

Literally, of course, differentiation also includes the development of differences in a magmatic body where this has melted up or assimilated

[1] A. Harker, The Natural History of the Igneous Rocks, New York, 1909, p. 309. J. P. Iddings, Igneous Rocks, New York, vol. 1, 1909, p. 251. G. W. Tyrrell, Principles of Petrology, London, 1926, p. 148.

[2] F. von Wolff, Der Vulkanismus, Stuttgart, vol. 1, 1914, p. 160. A. Osann in H. Rosenbusch, Elemente der Gesteinslehre, 4th ed., Stuttgart, 1923, p. 43. L. Milch, Geol. Rundschau, vol. 15, 1924, p. 318. *Cf.* O. H. Erdmannsdörffer, Grundlagen der Petrographie, Stuttgart, 1924, p. 206.

foreign material, solid, liquid, or gas. Yet to widen the meaning to that extent would ruin the term for practical use.

Several handbooks in English define the word on the assumption that the differentiating magma is initially homogeneous. However, probably no rock melt whatever is perfectly homogeneous. Assimilation, pure melting, and gas fluxing, which lead to the local formation of secondary solutions within a body of eruptive magma, are among the demonstrated causes of heterogeneity. The resulting composite bodies of liquid may be specially liable to rearrangement by gravitational or other forces, acting on liquids or eventually on crystals. In this way, part of the composite product of such incorporation becomes separated or "differentiated" from the remainder.

The present chapter attempts little more than a statement of opinion concerning the relative geological importance of the various modes of differentiation. For broad treatments of the subject, especially the physicochemical principles involved, the reader is referred to the writings of Teall, Iddings, Zirkel, Schweig, Loewinson-Lessing, Harker, Elsden, Brögger, and Clarke, and, among the more recent discussions, those of Berg, Boeke and Eitel, Bowen, Erdmannsdörffer, Goodchild, Niggli, Shand, Tyrrell, and Vogt, as well as the papers from a symposium conducted by the Faraday Society in 1925.[1]

Units of Differentiation

The complexity of the subject, as illustrated in an eruptive province or even a single batholith, is at once suggested by a list of the unitary masses that are capable of mutual separation in or from a natural magma. The units naturally exist in pairs. Their listing in Table 39 does not include the case of an initially heterogeneous, wholly primary magma. Liquid of that kind may have participated in the formation of the original earth shells. Moreover, if, as seems probable,

[1] J. J. H. Teall, British Petrography, London, 1888. J. P. Iddings, Bull. Phil. Soc. Washington, vol. 12, 1892, pp. 89–213; and Igneous Rocks, New York, 1909. F. Zirkel, Lehrbuch der Petrographie, Leipzig, vol. 1, 1893, pp. 711–796. M. Schweig, Neues Jahrb. f. Mineralogie, etc., B.B. 17, 1903, p. 516. F. Loewinson-Lessing, Compte Rendu, 7th session, Cong. Géol. Internat., St. Petersburg, 1899, pp. 308–401 (a remarkably well-balanced memoir). A. Harker, The Natural History of Igneous Rocks, New York, 1909. J. V. Elsden, Principles of Chemical Geology, London, 1910. F. W. Clarke, The Data of Geochemistry, 5th ed., Bull. 770, U.S. Geol. Survey, 1924. G. Berg in F. Behrend and G. Berg, Chemische Geologie, Stuttgart, 1927. H. E. Boeke and W. Eitel, Grundlagen der physikalisch-chemischen Petrographie, 2te Aufl., Berlin, 1923. N. L. Bowen, Jour. Geol., vol. 23, 1915, Supp.; vol. 27, 1919, p. 393; vol. 29, 1921, p. 295; vol. 30, 1922, pp. 177, 513. N. L. Bowen, Amer. Jour. Science, vol. 39, 1915, p. 175; vol. 40,

the Simatic substratum grows slowly more femic with increasing depth, disturbance and mixing of its sublayers may have generated during geological time some heterogeneous primary liquid which was erupted to undergo renewed differentiation. On the other hand, that part of the substratum which was specially engaged in Paleozoic and later petrogenesis appears to have had normally a high degree of uniformity in chemical composition.

TABLE 39.—UNITS OF MAGMATIC DIFFERENTIATION

Smaller Unit	Larger Unit
1. Molecule (and ion)	Surrounding magma
2. Crystal	Rest magma
3. Original magma modified by resolution of segregated crystals	(*a*) Rest magma and (*b*) original magma of same chamber
4 Non-consolute liquid fraction	Complementary non-consolute liquid
5. Localized mass of liquid, formed by pure melting of foreign rock by the original magma	Surrounding magma: (*a*) original, (*b*) modified by some diffusion of the secondary melt
6. Localized mass of hybrid liquid	Surrounding magma
7. Non-consolute gaseous fraction (bubbles)	Complementary liquid fraction

ABSTRACT OF THE FAVORED THEORY OF DIFFERENTIATION

Before discussing other views, the author will briefly indicate his own general position on the subject and thus perhaps help to prevent misapprehension.

The researches of Brögger, Vogt, Harker, and Bowen particularly have shown how fractional crystallization has to be considered as one of the dominant factors in differentiation, though unmixing in the liquid state may conceivably have affected the earth at its beginning. Further, there is some reason for assuming a basic liquid as the ultimate parent of all visible rocks. In Chapter IX, speculation, prompted by little more than the problem of the moon's origin and therefore with but weak sanction, led to the idea that the earliest

1915, p. 161. N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, with references to his earlier publications. O. H. Erdmannsdörffer, Grundlagen der Petrographie, Stuttgart, 1924. W. H. Goodchild, Mining Mag., sep., 1918. P. Niggli, Gesteins- und Mineralprovinzen, Berlin, vol. 1, 1923 (with long section by P. J. Beger); Lehrbuch der Mineralogie, Berlin, 1920; Die Leichtflüssigen Bestandteile im Magma, Leipzig, 1920. S. J. Shand, Eruptive Rocks, London, 1927. G. W. Tyrrell, Principles of Petrology, London, 1926. J. H. L. Vogt, Videns.-Skrifter, Oslo, Kl. I., No. 8, 1903; No. 1, 1904; No. 17, 1923; No. 15, 1924; No. 3, 1931. J. H. L. Vogt, Econ. Geol., vol. 21, pp. 207, 309, 469; Jour. Geol., eight papers in vols. 29–31, 1921 to 1923.

superficial shell of the earth was a heavy liquid, which by the settling-out of iron and perhaps magnesia compounds furnished a thick layer of more siliceous liquid at the earth's surface. Chemically this hypothetical derived liquid would also have differed from any of the standard rocks or lavas. Multiplied crustings and refusions, probably aided by "gaseous transfer," ultimately led to the separation of two sublayers: one chiefly granitic, above; the next below basaltic, passing downward into material approximating peridotite in chemical composition. The middle layer is assumed to have attained finally the composition of plateau basalt, much of which has been in the vitreous state since late Pre-Cambrian time. In spite of any previous changes of state, this glassy, eruptible shell is conveniently regarded as "primary."

While crystal fractionation is thought to have been a leading process in the production of rock species, remelting, selective fusion, and assimilation are also important. Here the author goes a step further than most petrologists are yet disposed to go and accepts fully the consequence of the fact that fractional crystallization is a more or less perfectly reversible process. A secondary liquid formed by pure melting or assimilation of rock in primary magma is necessarily heterogeneous, and the contrasted parts, though miscible if time were allowed, are differentiated by gravity before crystallization sets in. Lastly, the principle of gaseous transfer is retained among the working hypotheses, in connection with the development of some local bodies of rock, especially those rich in alkalies.

Suggested Mechanisms

1. Diffusion of Molecules and Ions.—The formation of a single crystal in a melt is a case of differentiation, so that diffusion of the molecular type is clearly involved in the general process. Thirty years ago, workers in the field thought that molecular diffusion has been capable of an enormously greater effect, namely, the development of cubic kilometers of chemically contrasted liquids or of solid *versus* liquid from a single body of magma. This view was the result of daring extrapolation from the principles of Soret (diffusion along a temperature gradient) and of Gouy and Chaperon (diffusive migration of molecules as such under gravity). Those principles had been shown to apply to dilute mobile solutions. Becker, Bowen, and others have shown that such diffusion to great distance can have no practical importance in the differentiation of individual magmatic bodies.[1]

[1] G. F. Becker, Amer. Jour. Science, vol. 2, 1897, p. 21. N. L. Bowen, Jour. Geol., vol. 29, 1921, p. 295.

2. Fractional Crystallization.—Since the days of Scrope (1825) and Charles Darwin (1844), petrologists have been familiar with the idea of the settling of early-formed crystals in solidifying magmas. After the year 1900, Schweig, Daly, and Harker stressed this obviously promising explanation of some magmatic differentiation, but until 1915 there was little response by many leading compilers of the theory of petrogenesis. In that year, Bowen began to publish the series of writings, which, being based upon careful experiments and able reasoning, have finally compelled general assent to the importance of fractionation by (1) gravity, as well as (2) zoning of crystals, and (3) filter pressing.

Bowen's theory, including his employment of the important "reaction principle," is so well-known that its detailed description is here not necessary. Space will be taken for a few comments on some principal points.

Gravitative Separation of Crystals.—The segregation of early-formed crystals, with the concomitant differentiation of liquid that contrasts chemically with the original liquid, is a process easily visualized. At first sight the required potential seems to be given automatically and to be sufficient for the generation of even large bodies of differentiated material. Yet this simple hypothesis has its own troubles. While Bowen's beautiful experiments prove the differentiation of artificial melts by the sinking of crystals and by the rising of crystals, the conditions of the actual process in Nature are not fully understood.[1]

A few intrusive sheets of diabase, including the Palisades, Tabankulu, and Tonti bodies listed in Table 40, have olivine-rich layers just above the respective chill phases at the floors. These mafic layers are commonly and reasonably regarded as due to the settling of early-formed olivines from the upper part of each sheet. Still more numerous sheets of general basaltic nature, though differentiated to a high degree and apparently by gravity, exhibit no such "olivine-diabase" or analogous layers. Examples are the Moyie River, St. Mary, Pigeon Point, East Duluth, Dolgelley, and Elands River sheets of Table 40. Each of these has a felsic differentiate near the roof,

[1] An account of the experiments may be found in the paper by N. L. Bowen (Amer. Jour. Science, vol. 39, 1915, p. 175). According to C. Neubauer (Földtani Kozlóny, vol. 41, 1911, p. 199), crystals of leucite, grown in certain artificial melts, were specially large and numerous at the upper levels, as if the leucites had risen and thus behaved like the tridymite crystals, also of relatively low density, in some of Bowen's preparations. A. Fersman (Geochemische Migration der Elemente, Abhand. prak. Geol., etc., Halle, vol. 18, Teil 1, 1929, p. 25) finds the rise of light, early-formed crystals, such as nephelite (*sic*) to be one condition for magmatic differentiation.

and, according to the hypothesis of fractional crystallization under gravity, much mafic material should have sunk toward the floors. The absence of marked, strongly mafic layers might be explained by resorption of sunken, early-formed crystals in a thick, deep-lying sublayer, though Bowen is not friendly to the idea. But, even if we do assume the resorption, the magma so enriched in femic material should itself be fractionated with the formation of a sublayer rich in olivine or pyroxene still lower down in each sheet. Thus crystal fractionation of quite uncontaminated primary magma does not appear to be the sole process involved in some clear instances of gravitative differentiation.

Many other thick sheets of nearly or quite basaltic composition are notably homogeneous from top to bottom. Examples are found among the Purcell sills of British Columbia and the Karroo dolerites of South Africa. According to Phemister, the 300-meter sill at Cobalt, Ontario, had become only very slightly differentiated before it solidified.[1] Why did the crystals early formed in these thick masses not segregate under gravity? If Bowen is right in holding that batholiths of mafic granite, granodiorite, and quartz diorite are not of eutectic composition, why do they show so few evidences of the settling of early-formed crystals and consequent systematic change of chemical composition in their vertical sections?

The apparent answer is prohibitive viscosity of these magmas, whether basic or acid, supplemented, of course, by true strength as the melts approached complete crystallization. Wherever, then, crystals have clearly sunk in magma, we may assume that the liquid was specially conditioned; it must have had comparatively low viscosity and negligible strength for some time. One conceived cause for the mobility is unusual abundance of volatile matter. Accordingly, at volcanic vents of the central type—loci of concentration of hot gas—this simple kind of crystal fractionation seems probable. Again, since alkali-rich magmas carry much volatile matter, their fractionation by gravity might be advanced in spite of small thicknesses for the respective bodies. Examples may be those of the Shonkin Sag laccolith, the Lugar sill, and the Garbh Eilean sill (Shiant Isles).

Grout's picture of crystal fractionation seems worthy of attention. He points out that, during much of the magmatic stage of a thick igneous body, crystals are locally concentrated along wall and roof,

[1] T. C. Phemister, Trans. Roy. Soc. Canada, vol. 22, 1928, pp. 121, 157. For general discussion of the subject, see L. V. Pirsson, Bull. 237, U.S. Geol. Survey, 1905, p. 184; C. N. Fenner, Jour. Geol., vol. 34, 1926, p. 745; L. Milch, Geol. Rundschau, vol. 15, 1924, p. 333.

rather than distributed uniformly throughout the mass. This crystal-sown phase is probably denser than the unmodified liquid. If the group of crystals settles down a short distance into the unmodified liquid beneath, the mixture has density higher than the original liquid where free from crystals. Hence each local mixture tends to sink. The downward-shearing stress of the denser body of material increases with the square of the diameter of that body, which, even if only a meter in diameter, may sink much more rapidly than any isolated crystal. The result is a powerful two-phase convection of a special kind.[1]

Thus any residual liquid caught in the sinking mass is dragged down to levels where crystallization has not yet affected the original magma. Nevertheless, this residual liquid, though more or less mixed with the original magma, is the lighter and tends to rise again. Reaching the cooler zone, the liquid begins to crystallize in its turn—to supply still more salic residual liquid to the lower levels, again to be cleansed by gravitative adjustment. Integration of such effects may be conceived to result in thorough gravitational differentiation of considerable masses of magma. Grout's type of two-phase convection seems to be a worthy competitor, in theory, with the filter-press mechanism (see below).

Differentiation by the sinking or rising of individual crystals is a process necessarily completed during an early stage in the solidification of a magma. To this stage, accordingly, may be referred the formation of such rocks as oceanite and ankaramite with the complementary fractions, all from basaltic liquid. So also Bowen explains the derivation of the Porphyritic Central types of lavas in Mull from basalt.[2]

Filter Pressing.—Since 1919, Bowen has stressed the squeezing-out or filter-press mechanism which had been described by Scrope, Jukes, Barrow, and Harker.[3] Residual liquid is supposed to be segregated by external pressure of the orogenic type. Strongly alkaline liquids, including the phonolitic and trachytic, are taken to be the products of such squeezing of chambers, these being initially charged with less alkaline magma. Yet many trachytic and phonolitic bodies show evidence of having been differentiated from basaltic liquid at volcanic centers where orogenic pressure seems not to have operated during the separation. Examples are found in the oceanic islands, and among

[1] F. F. Grout, Jour. Geol., vol. 26, 1918, p. 491.

[2] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 136.

[3] See A. Harker, The Natural History of Igneous Rocks, New York, 1909, p. 323; J. P. Iddings, Bull. Phil. Soc. Washington, vol. 12, 1892, pp. 100, 102; S. Foslie, Jour. Geol., vol. 29, 1921, p. 714.

the continental volcanoes which were built since their respective regions had been last affected by mountain building.[1]

Filter pressing may be conceived as due to internal as well as external causes. For example, the filtration may be produced by the weight of the crystal mesh when a magmatic body approaches complete solidification but still contains residual liquid. In general, the average density of the mesh of touching crystals is greater than that of the residual liquid. Near the bottom of the chamber the denser material of the mesh tends, by its own weight, to squeeze the liquid out and upward. Should not the theory of crystal fractionation be extended to cover this case? Are some pegmatites so formed?[2]

Crystal Fractionation and Thermal Convection.—A fourth suggested method by which fractional crystallization may cause differentiation involves thermal convection. This hypothesis was announced by Becker and elaborated by Pirsson, who applied it to the case of the Shonkin Sag laccolith. For physical reasons, given in "Igneous Rocks and Their Origin," Pirsson's version is not acceptable. Since most petrologists now agree with this conclusion, the argument need not be fully repeated. The possibility of thermal convection depends upon the fourth power of the thickness of the liquid concerned; hence the assumption of thermal convection in a mass as thick as the Duluth gabbro is not so open to criticism. There, however, one may well doubt that the circulation would be of the type imagined by Becker, Pirsson, and Grout.[3] The case at Shonkin Sag will be considered in a later section of the present chapter, page 341.

Quantitatively considered, the role of crystal fractionation in any or all of its forms cannot be stated until all other causes of magmatic differentiation have been similarly weighed. To regard the latter

[1] N. L. Bowen (Jour. Geol., vol. 33, 1925, p. 828) explains the differentiation of the Sudbury sheet, Ontario, by squeezing under the horizontal pressure which he believes to be indicated by the existing basin structure. Yet many other intrusive sheets bearing differentiates of the same chemical types are flat and, when liquid, were evidently not affected by orogenic pressure.

[2] Essentially the same suggestion seems to have been made, in principle, by H. H. Thomas and E. B. Bailey (Mull memoir, Geol. Survey Scotland, 1924, p. 330). Analogous is the migration of petroleum out of sediments, enforced by the weight of the sediments which thereby become more compacted. This process has been experimentally imitated. See M. G. Cheney (Bull. Amer. Assoc. Petroleum Geologists, vol. 13, 1929, p 559).

J. H. L. Vogt (Skrifter Norske Videns. Akad. Oslo, Kl. I, 1929, No. 6, p. 8) thinks that differentiation by squeezing is possible even when 45 per cent of the melt is still liquid.

[3] G. F. Becker, Amer. Jour. Science, vol. 4, 1897, p. 257. L. V. Pirsson, Bull. 237, U.S. Geol. Survey, 1905, p. 187. F. F. Grout, Jour. Geol., vol. 26, 1918, p. 499.

as demonstrably negligible, especially the several mechanisms by which magmatic liquids become separated from magmatic liquids (cases 4, 5, and 6 of Table 39), is not warranted by present knowledge.

3. Rest Magma versus Magma of Resorption.—Before passing on to the quite contrasted hypotheses, we may pause to consider a by-product of the one just discussed. If the temperature is right, sunken early-formed crystals are redissolved at the deeper, hotter levels of the magma chamber. Schweig, Berg, Vogt, Erdmannsdörffer, Tyrrell, Beger, Niggli, Scheumann, Sokol, Burri, and others accept the possibility of such re-solution within a magmatic body.[1]

Since crystallization begins along the walls of the chamber, three different kinds of liquid may be developed within it. These are: magma as yet unaffected by crystallization or re-solution of crystals sunk into it, magma residual from partial crystallization along the walls, and magma modified by the re-solution of sunken crystals. Necessarily these three parts of the liquid have contrasted densities, and, though perfectly miscible if given opportunity, they tend to separate by gravity before mixing with any thoroughness. Once arranged according to density, the liquids crystallize long before diffusion can effect any later notable intermixture.

4. Liquid Immiscibility.—"Igneous Rocks and Their Origin" emphasized the hypothesis of unmixing in the liquid state. It was suggested that the substance of a solid crystal might conceivably be concentrated within the liquid before the solid phase appears, and that these molecular concentrates, like liquid crystals, might separate gravitatively into layers. This speculation, inherited from some of the old masters in petrology and apparently supported by the results of certain experiments by Richards, Ostwald, Slaowratsky and Tammann, Dittler, Schade, von Weimarn, and Buchanan, is now seen to have little direct sanction. Vogt accumulated evidence against the idea in the case of silicate solutions. Greig has demonstrated liquid unmixing for special, "dry" silicate melts at very high tem-

[1] M. Schweig, Neues Jahrb. f. Mineralogie, etc., B.B. 17, 1903, p. 563. G. Berg in F. Behrend and G. Berg, Chemische Geologie, Stuttgart, 1927, p. 75. J. H. L. Vogt, Videns.-selsk. Skr., Kl. I, Oslo, No. 17, 1924, p. 17. O. H. Erdmannsdörffer, Grundlagen der Petrographie, Stuttgart, 1924, p. 211. G. W. Tyrrell, Principles of Petrology, London, 1926, p. 157. P. J. Beger and P. Niggli in P. Niggli's Gesteins- und Mineralprovinzen, Berlin, 1923, vol 1, pp. 27, 474, 561. K. H. Scheumann, Centralbl. f. Mineralogie etc., 1922, p. 519; R. Sokol, Chemie der Erde, vol. 1, Heft 4, 1919, p. 419; C. Burri, Verhand. Schweizer Naturf. Gesell., 1931, p. 315. L. L. Fermor (Rec. Geol. Survey India, vol. 66, part 1, 1932, p. 20) concludes that the Deccan flows of oceanite, ankaramite, and limburgite were derived from normal basaltic liquid but crystallized from melts of their own composition.

peratures, but with reason doubts that these abnormal solutions behave like ordinary magmas. Bowen's latest argument against the hypothesis of liquid unmixing is powerful.[1]

Nevertheless, in spite of negative evidence in field or laboratory, some authorities refuse to give up the idea of liquid unmixing in normal silicate magmas. Thus Evans, like Arrhenius and Richardson, believed immiscibility may appear

> . . . when there is a large amount of water or other volatile constituent present, which at the temperature of igneous magmas can assimilate some of the compounds in the magmas more easily than others. For instance, there is reason to believe that water vapour under high pressure can dissolve silica, the aluminates of the alkalies, and muscovite, that is to say material having the composition of an acid granite, to a very considerable amount, but not so easily the silicates of the divalent metals, which are the chief constituents of the more basic rocks.[2]

According to Johnston, we cannot as yet exclude the possibility that liquid unmixing may be caused by change of pressure.[3]

Read and Summers think the question remains open. Asklund prefers limited miscibility to fractional crystallization as a basis for explaining the differentiation of granites, norites, quartz diorites, and quartz syenites in the Stavsjö region, Sweden. Sundius concluded that two contrasted aplitic magmas in dikes of the Loftahammar massif, Sweden, separated from each other in the liquid state. Niggli states that we have no data opposing the hypothesis in the case of hydrous melts, while Grout here positively favors it. According to Lodochnikow, it should not be rejected as worthless until much more experimental work on silicates has been done.[4]

[1] J. W. Greig, Amer. Jour. Science, vol. 13, 1927, pp. 1, 133, 148. N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, Chap. 2.

[2] J. W. Evans, Trans. Faraday Soc., vol. 20, 1925, p. 465, and (W. A. Richardson) p. 444. A. Scott (*ibid.*, p. 495) offers a modification of the Evans hypothesis. S. Arrhenius, Geol. Foren. Förh. Stockholm, vol. 22, 1900, p. 417.

[3] J. Johnston, Jour. Geol., vol. 23, 1915, p. 740.

[4] H. H. Read, Geol. Mag., vol. 6, 1919, p. 368. H S. Summers, Proc. Roy. Soc. Victoria, vol. 26, 1913, p. 291. B. Asklund, Arsbok. Sver. Geol. Unders., vol. 17, No. 6, 1925, p. 106. N. Sundius, *ibid.*, vol. 19, No. 3, 1926, p. 30. P. Niggli, Neues Jahrb. f. Mineralogie, etc., 1914, vol. 2, p. 94; *cf.* Chemie der Erde, vol. 1, Heft 2, 1914, p. 20. F. F. Grout, Econ. Geol., vol. 13, 1918, p. 195; Jour. Geol., vol. 26, 1918, p. 657. W. N. Lodochnikow, Matériaux, comité géol., Leningrad, Livr. 69, 1927, p. 100. E. Wiman (Bull. Geol. Inst. Upsala, vol. 23, 1930, p. 127) retains liquation as a working hypothesis in partial explanation of the igneous complex around Upsala. G. W. Tyrrell (Proc. Geol. Soc. London, No. 990, 1916, p. 55) favors liquid unmixing in the Lugar sill. T. Krokström (Bull. Geol. Inst. Upsala, vol. 24, 1932, p. 197) inclines to accept the same mechanism for the separation of dolerite and granophyre in the Breven dike.

Evidently the subject is not one for dogmatic assertion. Although the greater weight of opinion appears to be decidedly opposed to the idea of liquid unmixing in silicate magmas, high authorities are here still keeping an open mind. We have already noted the question whether this process was important during the primeval development of the earth's outer shells.

On the other hand, the principle is well established in the case of silicate-sulphide solutions, both artificial and natural (magmatic). Berg thinks that it probably holds also with silicate-oxide magmas.[1]

5. Pure Melting and Differentiation.—For convenience the possible conditions for the refusion of rocks—a topic of the last chapter—may again be listed:

1. Downstoping of xenoliths to levels of relatively high temperature. The xenoliths may be (*a*) of moderate size and either felsic or mafic, or (*b*) big crust blocks of major stoping, composite but largely felsic.
2. Orogenic bending of the crust downward, deeply into the substratum.
3. Special radiothermal heating.
4. Fusion by magma erupted into the crust, (*a*) the magma being saturated, but the solid rock either as a whole or in part having a lower temperature of melting, (*b*) the magma being somewhat superheated.
5. Intermittent convection in substratum or large basaltic injection, whereby rock crystallized above is remelted by the heat of the risen basaltic liquid.
6. Local gas fluxing (*a*) by upstreaming gases charged with much of the original temperature of deep-seated magma, (*b*) by transfer of heat through two-phase convection (see page 367), (*c*) by heat developed through chemical reactions among the concentrated gases.

Remelting by any of these methods gives liquids of comparatively low density, whether the rock affected is felsic or as mafic as basalt or gabbro. Of the basic rock the first fraction to melt includes the alkaline parts of the crystals that, along with volatile components, had separated late during the original crystallization. Such secondary melts, formed at some depth, tend to rise through the primary basaltic magma. Its local diffusive mixture with them produces hybrid magma and this too tends to rise in the pure basaltic liquid. Thus large volumes of secondary, relatively salic magma come to overlie the uncontaminated basalt and actually invade the upper levels of the crust. The liquid layers so gravitatively formed are stable in spite of their complete miscibility; mixture by diffusion is insignificant before crystallization brings it to a complete stop.

[1] G. Berg in Behrend and Berg, Chemische Geologie, Stuttgart, 1927, pp. 98, 139, 155.

This general conception has no place in most published theories of the origin of batholiths; yet it seems necessary to hold it among the alternative explanations (see pages 312, 403, 424, and 461).[1]

Other possible examples of the same principle are found among the comparatively alkali-rich basalts and their allies. The origin of these rocks is discussed in Chapter XVI, where it is suggested (*a*) that they essentially represent plateau basalt to which a moderate amount of the alkalies (largely feldspathic material) was added; (*b*) that in each case the added material originated in the syntexis of residual volatiles with the more alkaline crystals of holocrystalline xenoliths or wall rocks of general basaltic nature; and (*c*) that the partial remelting was accomplished at some depth in the column of liquid plateau basalt, the relatively less dense, foreign solution rising through the column and enriching it with the alkalies at a higher level.

This hypothesis seems to account better for the rocks mentioned (all occurring in small volumes) than does the hypothesis of straightforward crystal fractionation in a single course.

6. Assimilation and Differentiation.—We can hardly doubt that liquid and gaseous syntectics must separate gravitatively from the assimilating host magmas. The density differences are normally sufficient to provide the required shearing stresses, and the more salic, syntectic liquid comes to overlie, though transitionally, the less contaminated part of the magma. And here too the system is practically stable.

7. Gases and Differentiation.—By pneumatolytic action, silicates and other compounds of low volatility are transferred from natural melts. These substances are dissolved in the dominant volatile gases and doubtless, by chemical combination, make with some of the gases even more complex molecules. Such compounds, sharing in the volatility, are removed from the rest of the magma. This principle of "distillation" has been particularly emphasized by Niggli.[2]

According to Fenner, "gaseous transfer" was important at Mount Katmai. The gases reacted with the constituent minerals of the solid rocks "in such a way as to form volatile compounds. . . . There is evidence of the transportation of material in the gaseous medium." Fenner accepts also the possibility of similar gaseous transfer of material inside a magmatic body. He writes:

[1] P. Eskola (Min. u. Petr. Mitt., vol. 42, 1932, pp. 474, 477) suggests that big masses of older granites at depth have been remelted entirely and intruded at higher levels. The Hango granites of southern Finland are regarded by him as of this origin, which, however, he regards as "exceptional."

[2] P. Niggli, Jour. Amer. Chem. Soc., vol. 35, 1913, p. 1726; Trans. Faraday Soc., vol. 20, 1925, p. 433; Die Naturwissenschaften, Heft 45, 1916, p. 686; (with P. J. Beger) Gesteins- und Mineralprovinzen, Berlin, 1923, vol. 1, p. 568.

Without attempting to determine the source from which the gas emanates, however, we may favorably entertain the tentative view of most volcanologists that there is probably a streaming of gases through the magma reservoir from lower levels toward the surface, some of it escaping through volcanic conduits and some penetrating the rock walls, and we may inquire into the consequences of this conception.

The equilibrium in a mixture of gases is dependent upon the temperature and pressure. The differences of pressure between the lower and upper levels of a large magma body must be very great. In the ascent of a gas bubble, reactions among its constituents will ensue, of such sort as to increase the molecular numbers. Reactions with the surrounding magma will likewise take place. Some substances will be given up to the magma and others taken into gaseous solution. When the gas finally escapes, its composition will be different from what it was at lower levels. The effectiveness of magmatic gases as agents of differentiation, therefore, lies both in their ability to carry away material entirely when they escape, and in their ability to make selective transfer of material from lower to upper levels.[1]

Fenner thus assumes the gases responsible for this kind of differentiation, to form a separate, bubble phase, the de-solution being in part due to change of pressure with eruption from depth.

The last chapter holds the thesis that much resurgent gas may be added to the juvenile gas of a primary melt. Both kinds of volatile material are concentrated in the residual liquid as the melt slowly crystallizes, and it is at least possible that resurgent gas enters magma in excess of its solubility in that magma. Naturally, too, the change of pressure as a magma rises into the crust must be considered as a cause of effervescence and therefore of concentration of gas through the rise of bubbles. The same effect may be looked for, if the magma is stirred by convection currents which involve changes of pressure. Another condition for the development of free gas in a chamber is pure molecular diffusion of the gas to loci of least pressure.

Whether bubbles form in comparatively deep-seated magmas is a difficult question. According to Eskola, the dikes of Sviatoy Noss carried bubbles at the depth of more than 1000 meters, and some analogous cases can be cited.[2] Yet no such list of itself could demonstrate how efficient gaseous transfer may be. Gillson accepts Fenner's conception of movement in the bubble phase and offers it in explanation of strongly alkaline rocks as differentiates of granitic magma.[3]

[1] C. N. Fenner, Jour. Geol., vol. 34, 1926, p. 743. E. T. Allen of the Geophysical Laboratory at Washington (Bull. 61, Nat. Research Council, Washington, 1927, p. 260) writes: "It is difficult for a chemist to imagine a gas leaving the depths and finding its way to the surface without being contaminated by the volatiles resident in the various rocks and strata through which it must pass."

[2] P. Eskola, Finska Vetens.-Soc. Förh., vol. 63, 1920–1921, Afd. A, No. 1, p. 11.

[3] J. L. Gillson, Jour. Geol., vol. 36, 1928, p. 471.

Similarly, von Eckermann accounts for the differentiation of a Swedish lamprophyre, "hamrongite," by the action of "high-pressure-bubbles."[1] According to Barth, the plumasite and canadite of the Seiland dike magmas originated by mutual unmixing in the liquid state. The plumasite represents a *flüssige* submagma and the canadite a *fluiden* magmatic phase (Dampf-Phase).[2] Holmes and Harwood think that gaseous transfer has led to the trachybasalt-trachyte association of oceanic volcanoes.[3] Although the French petrologists have long been foremost in emphasizing the gaseous transfer of the alkalies, it is not clear that they in general have believed this process to take place within magmatic bodies when still liquid. According to Bowen, the concentration of the alkalies in a liquid magma by moving, free gas is of little or no importance, and to assume it is to put the cart before the horse, for such concentration of the alkalies normally accompanies the "silicate transfer of the volatiles."[4]

Summary.—Amid so many uncertainties one truth stands fast: the more closely the process of differentiation is considered in terms of its possible or probable units, the more unsafe is the reference of the diversity among igneous rocks to only one mode of origin or any one mechanism of separation. From first to last we have the insistent question as to *what* is differentiated, to form either a single composite body or a geographically related series of separate eruptives—the rocks of a petrographical province. If, as the author holds, a proper theory of the earth demands assimilation and pure melting, both on the comparatively large scale, as well as gas fluxing, we should allow for important differentiations among liquid fractions—and this quite apart from the question of spontaneous unmixing of liquid fractions in originally homogeneous, primary magma. With Bowen, and now Harker, Smyth, and others, we may agree that the only post-Cambrian primary magma has been basic and the author regards it as dominantly basaltic. Moreover, it is clear that fractional crystallization of uncontaminated basalt is theoretically capable of developing a number of rock types which are like those actually found in Nature. But the rating of that explanation of the igneous rocks alongside of a half dozen other competitive explanations appears to be out of the question. The same conclusion has been reached by Fenner:

> If we regard matters in as unbiased a manner as possible I think we shall have to admit that for most of the differentiated igneous bodies that have been studied there is not yet apparent any complete explanation as to the cause or

[1] H. von Eckermann, Fennia, vol. 50, No. 13, 1928, p. 18.

[2] T. Barth, Skrifter Norske Videns.,-Akad. Oslo, Kl. I, 1927, No. 8, p. 117.

[3] A. Holmes and H. F. Harwood, Miner. Mag., vol. 22, 1929, p. 49.

[4] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 293.

causes of variation. Gaseous transfer, crystallization differentiation, assimilation of foreign material, and mingling of magmas have apparently each played a prominent part in one or another described instance, but it is impossible to say what is the quantitative importance of any one of these in volcanism as a whole, or whether there may not be still other important processes.

It is much better to recognize this situation and be on the lookout for new evidence than to accept any one explanation as of universal applicability.[1]

Gravitative Differentiation

Electrical and magnetic forces have been vainly invoked to explain magmatic differentiation. On the other hand, the dominance of gravity as a separating force is quite clear. To realize this fully, an extensive statistical review of eruptive bodies is necessary. To some results of such a study we may now devote attention. Many intrusive masses with roof and floor show differentiation in place. Many others, less completely exposed, are reasonably thought to have been ruled by a similar process. Rarely can one reach any fixed conclusion as to the kind or kinds of units which separated. As we have seen, solid crystals, pairs of liquids produced by spontaneous unmixing, and also contrasted fractions of miscible liquids (developed by partial crystallization, or by assimilation, or by the pure melting of foreign rock) are all likely to separate through differences of density. Since we are not absolutely certain that units other than solid crystals were involved, we need a noncommittal name with which to refer to the simple, fundamental fact. Such a name, safely descriptive of the mechanism largely responsible for the diversity of the igneous rocks, is "gravitative differentiation."

Gravitative Differentiation in Sills and Laccoliths.—While assembling the facts on which a stable theory of petrogenesis is to be based, special weight is due to observations connected with concordant injections. From these we obtain first-rank data on the problem of differentiation in general. Their magmas, when differentiated in place, may reasonably be supposed to have obeyed the same laws as those governing magmatic differentiation on the much greater scale of the invisible depths. In fact, information coming from sills and laccoliths is probably the most telling of all, and in some important respects to be preferred to that coming from artificial melts.

The conditions for securing the critical data are seldom fully met. The injection should be thick enough to permit differentiation before cooling of the magma brings prohibitive viscosity. The roof and floor should be accessible. The attitude of the body at the time of emplacement should be known, at least approximately. The observer himself must be alive to the many-sided problem and thus be ready to make the

[1] C. N. Fenner, Jour. Geol., vol. 34, 1926, p. 770.

TABLE 40.—GRAVITATIVE DIFFERENTIATION IN CONCORDANT INJECTIONS

Locality	Character of body	Maximum thickness, meters	Rock species, in order of superposition
1. Sudbury, Ontario	Interformational sheet	3000+	a. Micropegmatitic granite, granodiorite, and quartz diorite b Intermediate types c Norite d. Sulphide-rich norite and sulphide ore
2. Gowganda Lake, Ontario	Four sills	15–150	a. Micropegmatite and soda-aplite b Diabase and gabbro
3 Rose Township, Ontario	Sill	160+	a. Soda-granite (micrographic) b. Diabase
4. Bridgland Township, Ontario	Sill	340	a Pegmatitic quartz diorite b Epidotic diabase c. Typical diabase d. Aschistic chill phase
5. Lake Dufault, Quebec	Eastern member of composite sill laccolith	? Thick	a. Graphic granite b. Aplite c Diorite
6. Oiseau River, Manitoba	Irregular interformational sheet	1500+	a. Quartz diorite b. Hornblende gabbro c Hybrid between b and d d. More mafic hornblende gabbro e. Augite gabbro f "Augitite," sulphide-bearing
7. Maskwa River, Manitoba	Sill	? Thick	(Top eroded) a Hornblende gabbro b Augite gabbro c "Augitite," sulphide-bearing
8. Moyie River, British Columbia	Four sills	10–320+	a. Abnormal, micropegmatitic granite b. Intermediate types c Hornblende gabbro
9. St. Mary, British Columbia	Sill	43	a Micropegmatitic granite b. Quartz diorite c. Gabbro
10. Bonner's Ferry, Idaho	Sill (with similar sills in vicinity)	240	a Granodioritic type b. "Diorite" (hornblende gabbro?)
11. Flathead River, Montana	Sill	?	a. Micropegmatitic granite b. "Diorite" (hornblende gabbro?)
12. Pigeon Point, Minnesota	Sill	180+	a. Micropegmatitic granite b. Transitional types c Gabbro
13. East Duluth, Minnesota	Sill	300+	a. Micropegmatitic granite b. Transitional types c. Gabbro
14. Duluth, Minnesota	Lopolith	? (6000+ ?)	a. Micropegmatite, granite, syenite b. Gabbro, norite, anorthosite c. Mafic norite, pyroxenite, dunite, magnetite ore

TABLE 40.—GRAVITATIVE DIFFERENTIATION IN CONCORDANT INJECTIONS.—(*Continued*)

Locality	Character of body	Maximum thickness, meters	Rock species, in order of superposition
15 Palisades, New Jersey	Sheet	300+	*a.* Diabase rich in micropegmatite *b.* Normal diabase *c.* Olivine-rich diabase *d.* Floor (chill-phase) diabase
16 Gettysburg, Pennsylvania	Sill	200–270	*a.* Micropegmatitic diabase *b.* Normal diabase *c.* Mafic diabase
17. Preston, Connecticut	Laccolith	1000+	*a.* Oligoclase granite *b.* Quartz-hornblende gabbro *c.* Gabbro
18. Dolgelley, Wales	Sills (?)	?	*a.* Granophyre, grading downward to *b.* Markfieldite, and (other bodies) *a.* Markfieldite, grading downward to *b.* Dolerite
19. Northern Trotternish, Skye	Several sills	?	*a.* Dolerite *b.* Picrite
20 Glen Orchy, Scotland	"Mass"	?	*a.* Felsic kentallenite *b.* More mafic kentallenite *c* Picrite
20*a*. Brannie Burn, Scotland	"Intrusion"	?	*a.* Kentallenite *b.* Picrite
21. Shiant Isles, Scotland	Sill	180+	*a.* Crinanite *b.* Olivine dolerite *c* Picrite
22. Easter Dalmeny, Scotland	Sill	70+	*a.* Analcitized teschenite *b.* Normal teschenite *c.* Picro-teschenite and picrite
23. Sinni Valley, Italy	Laccolith	300+	*a.* Granite, aplite *b.* Plagioclasite *c.* Gabbro *d.* Peridotite (serpentine)
24. Portuguese East Africa	"Intrusion"	630+	*a.* Granophyric dolerite *b.* Dolerite
25. Elands River, Transvaal	Sill	300+	*a* Felsite, granophyre *b.* Transitional types *c.* Quartz norite *d.* Norite
26. Namaqualand	Sheet	? "Thick"	*a* Micropegmatite *b* Dolerite
27. Insizwa Mountain, East Griqualand.	Sheet	900	*a* Micropegmatitic norite and gabbro *b.* Norite and gabbro *c* Olivine norite and olivine gabbro *d.* Sulphide-bearing gabbro
28. Tabankulu Mountain, East Griqualand.	Sheet	600+	*a.* Felsic norite, with micropegmatite *b.* Norite *c.* Olivine norite and olivine gabbro *d.* Picrite *e.* Dolerite (chilled floor phase)

TABLE 40.—GRAVITATIVE DIFFERENTIATION IN CONCORDANT INJECTIONS.—(*Continued*)

Locality	Character of body	Maximum thickness, meters	Rock species, in order of superposition
29 Tonti Mountain, East Griqualand	Sheet	750+	Essentially like Tabankulu
30 Ingeli Mountain, East Griqualand.	Sheet	1000	Essentially like Tabankulu
31. Mount Prospect, Transkei. ..	Sheet	360+	a "Dioritic" phase b. Transitional types c. Dolerite
32. Tsinan, China..	Laccolith	Thick	a. Quartz diorite b Gabbro
33. Ayabe, Japan	Laccolith	?	a. Quartz diorite b. Diorite c. Gabbro d. Diallagite
34 Tamba province, Japan .	Apparently laccolithic	?	a. Quartz diorite b. Gabbro
35. Hitachi province, Japan . .	Laccolith	?	a Quartz diorite and hornblende gabbro b. Hornblendite c. Cortlandtite
36. Shinumo, Arizona .	Sill	280	a. Syenite b. Diabase
37. Electric Peak, Yellowstone Park.	Sill	9	a Feldspathic, shoshonitic phase b. Augitic, absarokitic phase
38. Shonkin Sag, Montana .. .	Laccolith	45	a Leucite basalt porphyry (roof chill phase) b. Syenite c. Transitional types d. Shonkinite e Leucite basalt porphyry (floor chill phase)
39. Square Butte, Montana	Laccolith	350+	a. Syenite b. Shonkinite
40. Zinc Mountain, Ice River, British Columbia	Laccolith?	Thick	a. Sodalite syenite (sp. gr. 2.455) b. Nephelite syenite (sp. gr. 2.605–2.657) c. Ijolite (sp. gr. 2.892–3.091) d. Jacupirangite (sp. gr. 3.380–3.471)
41. Lugar, Scotland...	Sill	42	(Within sheath of older teschenite): a. Theralite b. Picrite c. Peridotite
42. Benbeoch, Scotland	Sill	?	a. Mafic theralite (kylite) b. "Kylite-picrite"
43. Castle Craigs, Scotland . . .	Sill	?	a. Nephelite teschenite b. Hornblende teschenite c. Picrite
44. Howford Bridge, Scotland.. .	Sill	?	a. Analcite syenite b. Essexite-dolerite
45. Loch Borolan, Scotland.	Laccolith	400+	a. Quartz syenite, granite b. Quartz-free syenite c. Nephelite syenite, borolanite, ledmorite

TABLE 40.—GRAVITATIVE DIFFERENTIATION IN CONCORDANT INJECTIONS.—(*Continued*)

Locality	Character of body	Maximum thickness, meters	Rock species, in order of superposition
46. Loch Alsh, Scotland	Laccolith (part of a composite)	100	a. Pulaskite and nordmarkite b. Shonkinite
47 Ilimausak, Greenland	Composite injection (in two layers)	Thick	Upper layer: a. Arfvedsonite granite b. Quartz syenite c Pulaskite Lower layer: a. Foyaite (chilled phase?) b. Sodalite foyaite c. Naujaite d. Lujavrite and kakortokite
48. Kola Peninsula, Lapland	Laccolith	1000+	a. Urtite, lujvarite, etc b. Chibinite, etc.
49. Mt. Dromedary, New South Wales.	"Laccolith"	1100	a. Banatite b. Porphyritic monzonite c. Monzonite d. Pyroxenite
50. Prospect Hill, New South Wales.	Sheet	100+	a. Essexite with soda-aplite segregations and veins b. Mafic essexite
51. Chibougamau, Quebec	Laccolith (?)	?	a. Anorthosite, gabbro b. Basic norite, pyroxenite, iron ores
52. Kiruna, Sweden.	Laccolith (?)	1500+	a Quartz porphyry (locally roofless?) b. Quartz porphyry rich in iron-ore inclusions c. Magnetite ore
53. Kiruna, Sweden	Laccolith (?)	1500+	a. Syenite porphyry b. Syenite porphyry richer in iron oxides
54. Solör, Norway	Laccolith (?)	?	a Gabbro b Titanic iron ore

critical observations. The records show how rarely these conditions have been fulfilled among the many individual occurrences of igneous rocks. Nevertheless, a number of concordant injections have been proved to show gravitative differentiation in place. They are listed in Table 40.

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The case of the "Braefoot Outer Sill" of Fifeshire, described after Table 40 was set up, is analogous to Nos. 21, 22, and 43. At its floor is a chill phase, basalt, which is successively overlain by picroteschenite, teschenite, dolerite-pegmatite, and a chill phase of basalt at the roof. All internal contacts are transitional.[1]

Harker is not satisfied that most of the bodies listed show gravitative differentiation in place. For him, sharp contacts between two associated rock types and the diking of one by the other mean successive intrusions from depth. He explains transitional types as due to "partial admixture" of magmas successively intruded and states that "clear instances of gravitative differentiation in sills and laccoliths of which I have direct knowledge are all in rocks which must represent very unusually fluid magmas, such as analcite-bearing Permian intrusions of Scotland."[2]

Yet local sharp contacts and the apophysal relation do not furnish adequate evidence. One phase, generally the more salic and gas-rich phase, of a differentiated sill or laccolith solidifies later than the complementary phase. Hence the liquid with the longer life may dike the phase already made rigid and may also be moved so as otherwise to exhibit sharp contacts with the latter. Relatively small strains of the body during crystallization can accomplish both feats. An illustration of the principle may be quoted from the Mull memoir, in a section dealing with ring dikes:

After crystallization had proceeded for some time, and had practically exhausted the magma as regards lime and magnesia, there still remained a residuum which retained its fluidity over a considerable range of temperature, so that there was, at this stage, a marked pause in the process of crystallization. Under such conditions, ample opportunity was afforded for migration of the

[1] R. Campbell, T. C. Day, and A. G. Stenhouse, Trans. Edinburgh Geol. Soc., vol. 12, 1932, p. 342.

[2] A. Harker, Jour. Geol., vol. 24, 1916, p. 554.

fluid residuum under stress during the extended period that elapsed before crystallization was completed.[1]

Harker's alternative hypothesis of successive intrusions is opposed by the law of chances; for it is highly improbable that each of so many series would on this hypothesis show the systematic arrangement of rock types according to density. Partly for this reason such cases as those of Sudbury and Loch Borolan, concerning which Harker has expressed special doubt, have been included in Table 40.[2] On the other hand, some sills showing vertical alternation of mafic and relatively felsic phases may well represent instances of differentiation just before injection. An illustration of this is apparently afforded by the Blackness sill, with picrite both overlain and underlain by teschenite.[3]

All of the plutonic families quantitatively important—granite, granodiorite, gabbro, anorthosite, syenite, foyaite, peridotite—are represented in Table 40, and also many of the rarer families—analcitic and leucitic types, essexite, theralite, teschenite, urtite, ijolite, jacupirangite, lujavrite, shonkinite, borolanite, magnetite ore, sulphide ore. The wide chemical range of the fifty or more species, excluding transitional species, proves the significance of these injections for petrogenetic theory.

[1] H. H. Thomas and E. B. Bailey, Mull memoir, 1924, p. 330. On page 96 we read: "Such auto-intrusion must be a common phenomenon from the very nature of the case"; with this judgment the author heartily agrees. Among others who have recognized the principle are N. L. Bowen (Jour. Geol., vol. 25, 1917, p. 225); T. C. Phemister (Trans. Roy. Soc. Canada, vol. 22, 1928, p. 165); F. F. Grout (Bull. Geol. Soc America, vol. 39, 1928, p. 561). *Cf.* R. A. Daly (Amer. Jour. Science, vol 43, 1917, p. 433).

H. C. Cooke (Museum Bull 30, Geol. Survey Canada, 1919, pp. 4, 23) regards the strong differentiation of the East Sooke gabbro of Vancouver Island as having occurred in place, yet makes the following note: "Obscure and contradictory intrusive relations are frequently found between the various subvarieties (differentiates), and even between the broader types. At one place, for instance, a certain type, characterized by a definite composition and texture, may be observed to have a faintly chilled edge at its contact with another type, to send off intrusive stringers into it, and to include fragments of it; whereas at another point of contact between the same two types these relations are reversed." Such reversal of relations is uncommon where two phases differ widely in composition but even here seems easily credible, provided the magmatic body was of large size, so that the different phases were locally liquid (because at contrasted temperatures) and were also unequally stressed for prolonged periods.

[2] As remarked on p 432, some of the differentiation of the Sudbury sheet may have been accomplished in depth before the injection at the visible horizon. So J. Phemister (The Geology of Strath Oykell, etc., Mem. Geol. Survey Scotland, 1926, p. 86) explains the mass at Loch Alsh as a composite laccolith, not as a simple laccolith differentiated in place, though throughout the body the various phases are definitely arranged from top to bottom in the order of increasing density.

[3] J. Flett, Summ. Prog. Geol. Survey Great Britain, 1930, part 3, p. 39.

Some of the bodies illustrate a principle now well recognized: on account of chilling, differentiation tends to cease earlier along the contact than in the central part of the body. The contact phase, a more or less continuous shell, thus represents the original magma or else its comparatively early differentiate. The other phases, inclosed by this shell, are products of later differentiation. Examples of such association have been described by Lewis (Palisades of New Jersey), by Jevons and others (Prospect Hill, New South Wales), and by Daly (Purcell sills of British Columbia and Idaho). Compare Fig. 107.

The same explanation applies to the chemical contrast of the sheath of leucite basalt porphyry inclosing the syenite and shonkinite of the Shonkin Sag laccolith of Montana.[1] The middle of the laccolith shows a section described by Pirsson as follows (top at *a*):

	Thickness, Feet (1 Foot = 0.305 Meter)
a. Leucite basalt porphyry	5
b. Dense shonkinite	5
c. Shonkinite	5–6
d. Transition rock	3
e. Syenite	25–30
f. Transition rock	15
g. Shonkinite	60–75
h. Leucite basalt porphyry	15
Total	140 (nearly)

Pirsson calculated the approximate average composition of the laccolith (column 3 of the following table). Column 4 gives the composition of the leucite basalt abundantly extruded in the Highwood Mountains. Columns 1 and 2 respectively show the compositions of the syenitic and shonkinitic differentiates.

	1	2	3	4
SiO_2	50 0	47 9	48.0	48.0
Al_2O_3	19.4	12.1	12 4	13.3
Fe_2O_3	3 9	3.5	3.5	4.1
FeO	2.7	4.8	4 7	4.2
MgO	2.2	8.6	8.3	7.0
CaO	5.0	9.4	9.2	9.3
Na_2O	3 6	3 0	3.0	3.5
K_2O	8 5	5.6	5 8	5.0

Pirsson explained the various rock types by a combination of crystallization, thermal convection, and settling out. The influence of convection seems to be an unnecessary postulate. An alternative

[1] R. A. Daly, Mem. 38, Geol. Survey Canada, 1912, p. 772. After field study Dr. C. H. Clapp has confirmed this conclusion.

conception is suggested by the chemical nature of the average rock of the laccolith. Let it be assumed that a leucite basalt magma, such as elsewhere in the region forms volcanic masses, was here injected. On all contacts of the laccolith, though particularly at its rim, this magma froze quickly. The interior part, longer fluid, was cooled until it

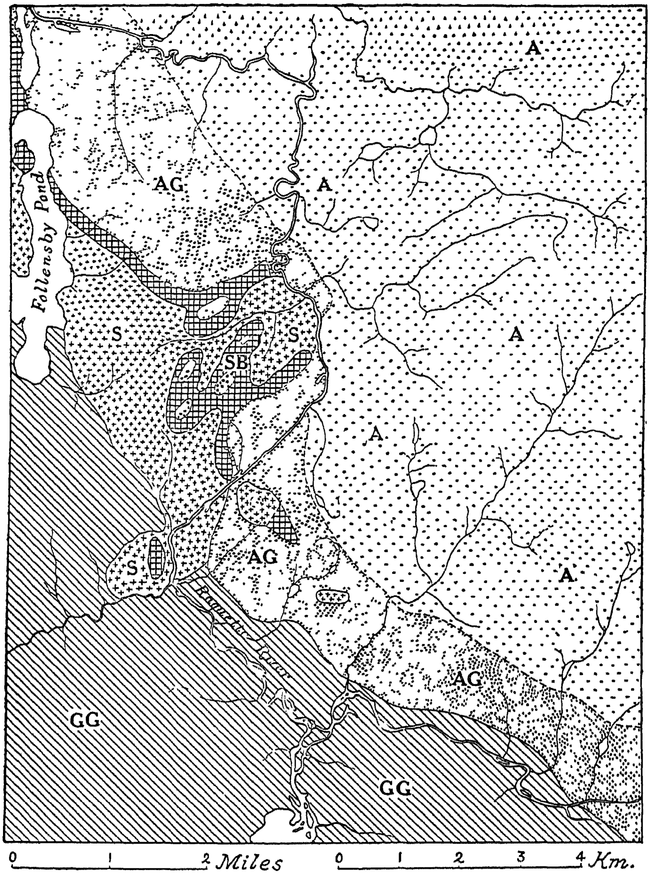

FIG. 107.—Map of part of the Long Lake quadrangle, New York State. *GG*, Grenville series of limestones and gneisses; *A*, anorthosite; *AG*, gabbroic contact phase of *A*; *S*, syenite; *SB*, basic phase of the syenite. *AG* appears to be a chill phase of *A*. (*After H. P. Cushing, Bull.* 115, *N. Y. State Museum*, 1907.)

reached the temperature of differentiation—yielding syenite above and shonkinite below.

The small chemical difference between shonkinite and leucite basalt would make it hard to prove that the "shonkinite" shells of *b* and *c* in Pirsson's section do not really form a granular continuation of shell *a*. All three shells seem, in fact, to represent the original

magma, which has differentiated in the center of the laccolith, giving shells *d*, *e*, *f*, and *g*. Analyses of *b* and *c* have not been published, but their analyses would fall within the limits of variation assignable to leucite basalt.

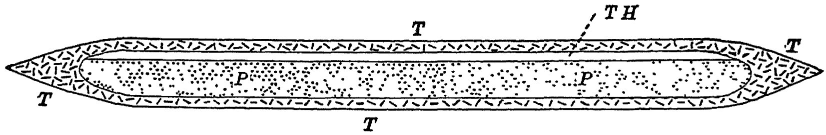

FIG. 108.—Diagrammatic longitudinal section of the Lugar sill. *TH*, theralite; *T*, teschenite; *P*, picrite. Length 5.5 kilometers; thickness 42 meters.

The same explanation is possible for the Square Butte laccolith, though the loss of its roof by erosion prevents a final test of the hypothesis in that instance.

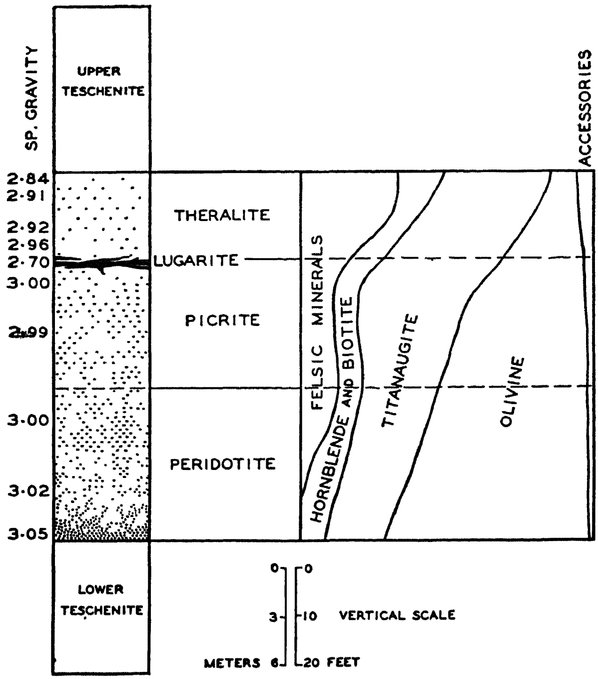

FIG. 109.—Vertical section illustrating differentiation in the Lugar sill. "The increasing density of the stippling represents increasing abundance of olivine crystals downwards. On the right is a diagram illustrating the increase in the amount of olivine in the differentiated part of the sill." (*From G. W. Tyrrell, The Principles of Petrology, London,* 1926, *p.* 151.)

Still another example, on a great scale, seems to derive from the gabbro-anorthosite mass of the Adirondack region, illustrated in Fig. 107.

As a rule, the chill phase at the roof and walls merges into the more felsic phase of gravitative separation. This relation has often been incorrectly described as "contact basification."

According to Tyrrell's revised conclusions regarding the well-exposed Lugar sill, we have there a case which at first sight appears to be like that of the Shonkin Sag body but is really contrasted in principle. The roof and floor phases are both teschenitic (Figs. 108, 109). These phases were split apart by a younger magma which, after this emplacement, differentiated by gravity into the following species, listed from above downward: theralite (sp. gr. 2.84 to 2.96), picrite (sp. gr. 3.00), and peridotite (sp. gr. 3.00 to 3.05).[1] In the section (Fig. 108) a single pattern covers both the picrite and the peridotite.

As a rule, the advance of gravitative differentiation in basic bodies is a function of their size. The thick Duluth, Sudbury, Ilimausak, and Chibougamau masses have yielded highly felsic and highly mafic rocks in each case. The thinner Purcell, New Jersey, Natal, Scottish, and Australian injections of more or less similar chemical composition, as well as the mass in the Preston district, Connecticut (Fig. 110), are less thoroughly differentiated. If, then, some batholiths are really abyssoliths and, when liquid, extended to the bottom of the crust, we can understand the homogeneous and felsic nature of the rocks at their outcrops, necessarily at high levels.

The remarkable differentiation of thinner, alkali-rich sheets, such as those at Shonkin Sag, Square Butte, Ice River, and Loch Borolan, we have already attributed to the low viscosity of their magmas, charged with volatile fluxes (see also Chapter XXI).

Many of the listed injections illustrate the "freezing-in" or "fixing" of small masses of one differentiate in the crystallized equivalent of its complementary magma. Thus the micropegmatitic phase of a Purcell, Sudbury, Minnesota, or South African sheet characteristically overlies a gabbroid or diabasic phase carrying interstitial micropegmatite or schliers or "veins" of the same material. These have evidently been trapped during the solidification of their respective hosts.

Rittmann explains the association of trachyandesite, trachybasalt, trachyte, and phonolite in the island of Ischia by assuming gravitative differentiation in a laccolith at moderate depth, the deformation of that body while still largely molten, and consequent eruption of material from different levels in the body.[2]

Gravitative Differentiation in Dikes.—Remarkable for its large scale is the density stratification of the ring dike at Glen More, Scot-

[1] G. W. Tyrrell, The Principles of Petrology, London, 1926, p. 151; Quart. Jour. Geol. Soc London, vol. 72, 1916, p. 123.

[2] A. Rittmann, Zeit. f. Vulkanologie, Erg. Heft 6, 1930, Fig. 40.

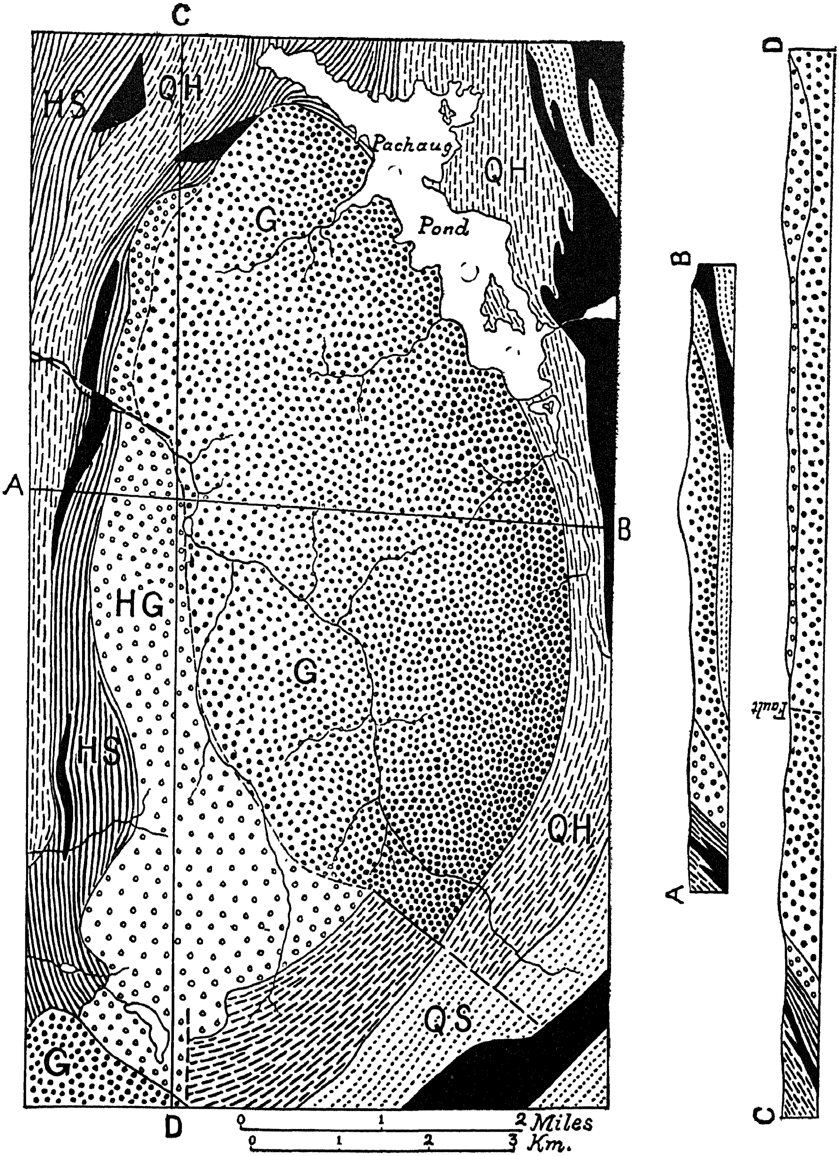

FIG. 110.—Map and sections of the gabbro laccolith at Preston, Connecticut. *QS*, quartz schist; *QH*, quartz and hornblende schist; *solid black*, Sterling granite gneiss; *G*, gabbro, *HG*, quartz-hornblende gabbro. *G* and *HG* are phases of the same laccolith. A general decrease of density, from the floor upward, is shown by varying closeness of the dots. (*After G. F. Loughlin, Bull.* 492, *U. S. Geol. Survey*, 1912.)

land (Fig. 111). Within a vertical distance of about 500 meters this body shows systematic gradual change upward "from gabbro through rocks of augite-diorite affinities to granophyre" (corresponding den-

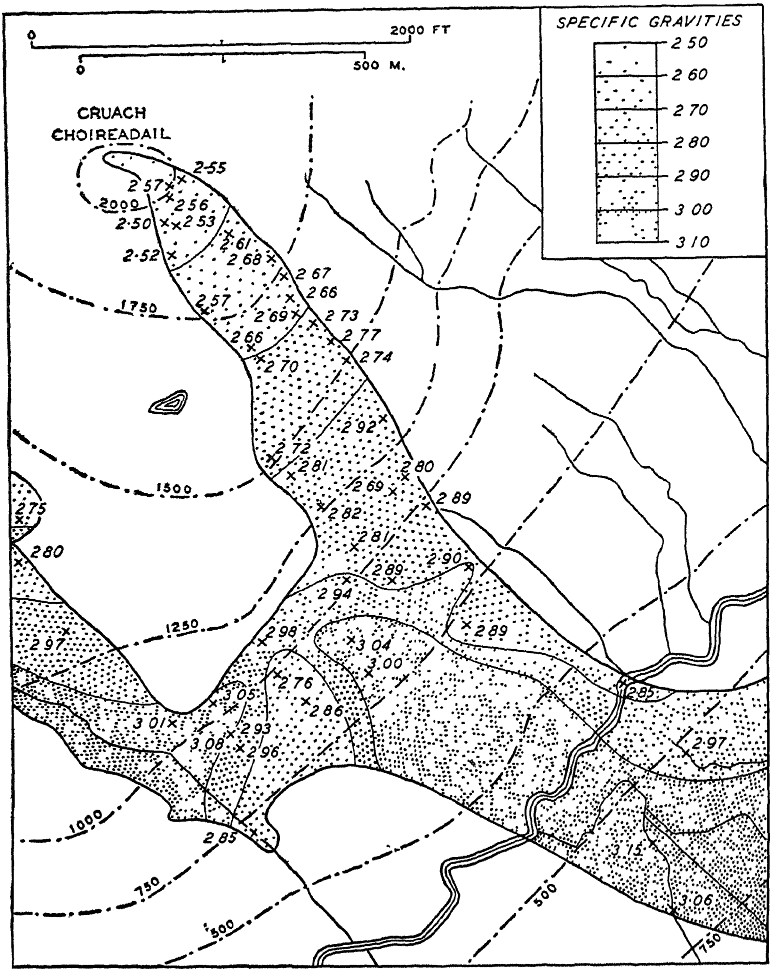

FIG. 111.—Map showing density stratification in differentiated ring dike, Island of Mull. The extreme products exposed are olivine-bearing quartz gabbro and granophyre. Contour interval in feet. (*After E. B. Bailey and others, Mull memoir, Geol. Survey Scotland*, 1924, *p.* 322.)

sities approximately 3.0, 2.8, and 2.5). Ten other dikes of Mull illustrate the same kind of differentiation.[1]

Gravitative Differentiation in Masses of Batholithic Habit.—If gravity is a controlling force in the differentiation of concordant

[1] E. B. Bailey and G. V. Wilson, Tertiary and Post-Tertiary Geology of Mull, etc., Memoir Geol. Survey Scotland, 1924, pp. 322, 330.

injections, it may be fairly considered as playing a similar role in subjacent bodies, but with more majestic results. Here the high-lying phase should be thick. It should be comparatively homogeneous because crystallized from anchi-eutectic liquid which is not likely to undergo much differentiation as it cools. That the separation of the visible felsic phase is indeed thorough is indicated by the rarity of its stratification according to density.

The Similkameen granite at the British Columbia-Washington boundary has been tested. Typical specimens were collected at each of two levels vertically 2000 meters apart. The average density at the higher level is slightly less than that of the rock 2000 meters deeper, but the difference is too small to permit any definite conclusion as to systematic stratification.[1] Knopf describes what appears to be a more positive instance of gravitative control in the visible section of a batholith. The quartz monzonite of Inyo County, California, has a specific gravity of 2.715 at the 2040-meter level and one of only 2.664 at the 3960-meter level.[2] Yet on the whole the evidence of stratification according to density in these great masses is negative. The simplest supposition is that many batholiths do extend downward to levels where the more mafic poles of their differentiation lie hidden. It may, then, be worth while to review once more the effect of gravity in the development of the liquids constituting the kind of batholith that has been theoretically distinguished as a major abyssolith.

a. The primary basaltic injection or the vitreous substratum itself is, in consequence of orogenic disturbance, contaminated by syntexis of more acid rock. The magmatic mixture undergoes progressive differentiation. If in succession satellitic bodies are erupted at levels accessible through erosion, these should be chiefly derived from the upper part of the major injection, and they should be formed in the order of increasing acidity. This is the sequence actually observed (see Appendix B of "Igneous Rocks and Their Origin").

b. The salic differentiate should vary chemically with the character of the average rock incorporated, whether by pure melting or by assimilation—an expectation actually met in the case of the concordant injections.

c. Toward the end of its long life, an abyssolithic magma becomes nearly or quite incapable of further incorporation of country rock. The partially differentiated liquid is chilled at roof and wall and there solidifies. Inside this contact shell the still-fluid magma continues to differentiate gravitatively. Hence at visible levels the interior of the mass should be more felsic than the chill phase (Fig. 112). The

[1] R. A. Daly, Mem. 38, Geol. Survey Canada, 1912, p. 475.

[2] A. Knopf, Prof. Paper 110, U.S. Geol. Survey, 1918, p. 67.

relatively basic contact phases would not be due to "contact basification," wrought by diffusion according to the Soret principle.[1]

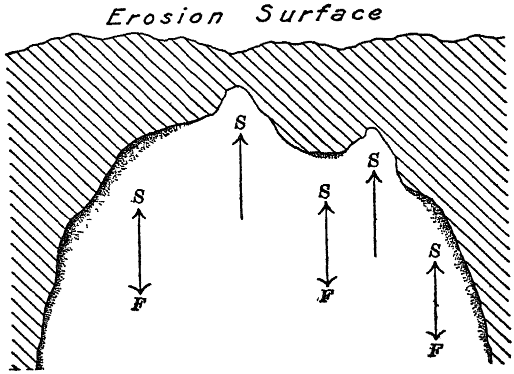

Fig. 112.—Diagrammatic section illustrating the development of contact phases in batholiths. *Dotted areas*, mafic phase; *blank area*, normal rock of batholith, *cross-lined*, roof and wall rocks. Double-headed arrows show directions of movement of salic (S) and femic (F) units of differentiation after crystallization of the chilled contact phase. Single-headed arrows represent the upward movement of salic material transferred by magmatic volatiles.

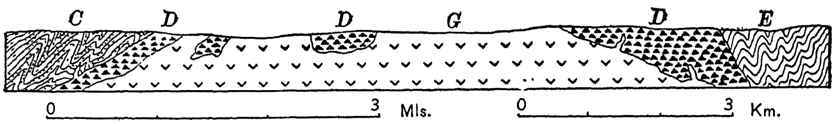

Fig. 113.—Syngenetic granite and diorite in the Penobscot Bay quadrangle, Maine. E, Ellsworth schist—Cambrian or Pre-Cambrian; C, Castine volcanics—Cambrian?; D, diorite and gabbro—Devonian?; G, granite—Devonian? The diorite appears to be an older, chilled phase of the batholith, in which the granite later differentiated and invaded the diorite. (*After Penobscot Bay folio, U. S. Geol. Survey*, 1907.)

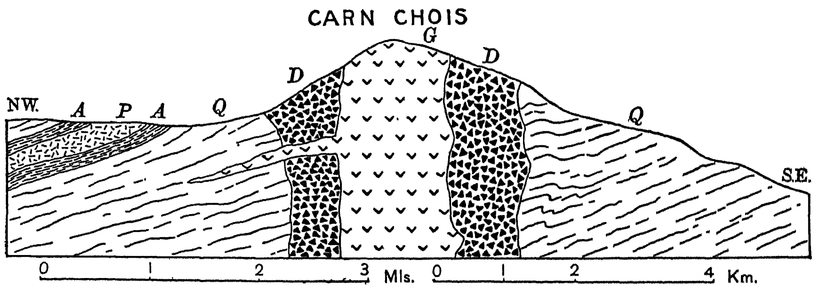

Fig. 114.—Section of the Grampian Hills stock. Q, quartzite etc.; P, porphyrite; A, amphibolite; D, diorite; G, granite. Essential relations probably the same as for the batholith of Fig. 113. (*After the Government map of Scotland*, 1893, *Sec.* 2.)

d. In many instances the contact phase, already crystallized, may be intruded by the central residual liquid. The renewed eruptivity

[1] The principle suggested in this paragraph seems to have abundant illustration in the "two-granite batholiths in the Pre-Cambrian," described by E. S. Moore and G. H. Charlewood (Trans. Roy. Soc. Canada, *iv*, 1930, p. 133).

is not unexpected if we consider the possibilities of massive readjustments in the abyssolithic chamber and also the corrosive power of the residual liquid. This relation is illustrated by Figs. 112 to 114. Another analogy, if not homology, to the speculative case of the abyssolith is represented in the Alta-Clayton stock of Utah, which has a dioritic chill phase and a younger granodioritic phase. Locally they are transitional into each other. Elsewhere they show sharp

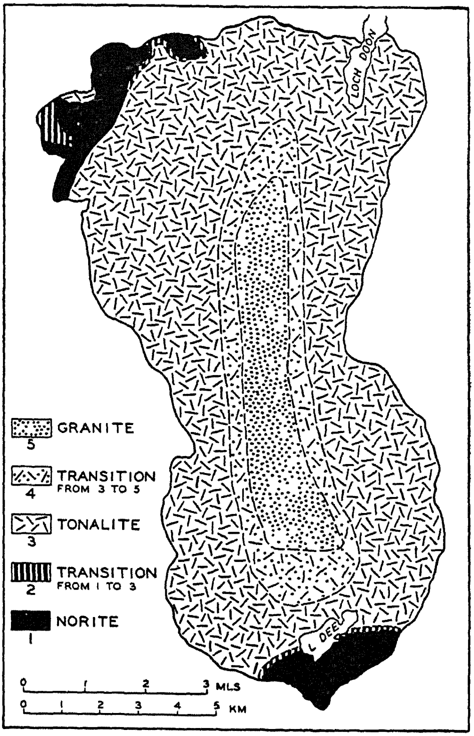

FIG. 115.—Map of the Loch Doon composite batholith, Scotland. Constituent intrusions numbered in chronological order. Average specific gravities: *1*, norite, 2.81 (94 specimens); *2*, tonalite, 2.72 (94 specimens); *3*, granite, 2.63 (27 specimens). See also Fig. 49. (*After Gardiner and Reynolds.*)

mutual contacts, and blocks of the diorite appear to be inclosed in the granodiorite.[1]

According to Gardiner and Reynolds, the Scottish Loch Doon intrusion is a composite laccolith, though it has characteristics of a composite batholith, as this word is defined in the present book. There is no field evidence of a floor (Fig. 115). The mass is composed of successive intrusions of norite, tonalite, and granite, the norite having been still hot when the tonalitic liquid made the visible contact with it,

[1] F. C. Calkins, Prof. Paper 111, U.S. Geol. Survey, 1920, p. 240.

and the tonalite itself having been "sufficiently liquid at the time of the granitic intrusion for a relatively wide band of hybrid and transitional rocks to be produced."[1] Although Gardiner and Reynolds are doubtful that the differentiation represented was *in situ*, the facts described suggest that the vertical displacement of the younger phases relatively to each other and to the older norite was moderate.

Gravitative Differentiation in Lava Flows.—Powers and Lane carefully studied the core from a drill hole sunk through a 170-meter flow of Triassic basalt at Cape d'Or, Nova Scotia. They found evidence of the settling of solid crystals of olivine and pyroxene. The top and bottom parts of the flow represent phases of quick chilling and therefore phases of the original magma. Lund describes an interesting parallel at Cape Spencer, Nova Scotia. The upper third of a 10-meter basaltic flow in Steens Mountain, Oregon, is free from olivine, while the lower two-thirds is enriched in that material. Fuller regards this case as one of crystal settling, but well localized and due to the sinking of the olivines from "an indefinite quantity" of very fluid basalt, as this lava continued to flow over the site of the accumulation of crystals. The reason why the crystals were dropped in special number at this particular spot is not given.[2]

Gravitative Differentiation in Volcanic Pipes.—Vélain stated that, during the 1874 eruption in the island of Réunion, a flow of andesite (sp. gr. 2.79) issued from the top of an active cone, while simultaneously a flow of olivine-rich basalt (sp. gr. 2.97) issued through a flanking fissure much lower down the mountain. This would be the only described case giving direct evidence of gravitative differentiation in a volcanic vent. Later field study by Lacroix has convinced him that Vélain had accepted an erroneous account of the event. The argument of Lacroix is based upon the chemical similarity of two specimens of lava (basalt) which was emitted in 1909 at the same vent—these specimens respectively representing glassy bombs thrown up at the summit of the cone and a flow which issued from a

[1] C. I. Gardiner and S. H. Reynolds, Quart. Jour. Geol. Soc. London, vol. 88, 1932, p. 17.

[2] S Powers and A. C. Lane, Trans. Amer. Inst. Min. Eng., February, 1916, p. 535, with references to other cases discovered by Lane among the Keweenawan flows of basalt. R. J. Lund, Amer. Mineralogist, vol. 15, 1930, p. 539. R. E. Fuller, Abstr. of papers, 43d meeting of the Geol. Soc. America, 1930, p. 41. *Cf.* L. L. Fermor, Rec. Geol. Survey India, vol. 58, 1925, p. 196.

B. S. Butler and colleagues (Prof. Paper 144, U.S. Geol. Survey, 1929, p. 26) found some of the Keweenawan flows and possibly all of them to show "a slight tendency toward the concentration of more basic material near the bottom by settling." The 60-meter Kearsarge flow, just beneath its amygdaloidal cap, exhibits a "zone from a few inches to several feet thick containing abundant feldspar phenocrysts that collected by rising from the underlying lava."

fissure halfway down; and it appears conclusive if the composition of the lava in the pipe during 1874 was actually identical with that standing there thirty-five years later.[1]

That gravity controls differentiation at central vents has some indirect evidence. The lavas of the summit cones of Mauna Kea, Hawaii, which are relatively feldspathic rocks and allied to trachydolerite and basic andesite, are differentiates of olivine-basaltic magma, the dominant material constituting the older flows of Mauna Kea. Quensel found the low-lying lavas of Masafuera, one of the Juan Fernandez Islands, to be normal basalts, succeeded above by basanitic lava which in turn is overlain by soda-trachyte.[2] The highly felsic trachytes of Tutuila Island, Samoa, fill pipes running up through a major basaltic cone. The ultrabasic lava that flooded the Leone shore of the island after the trachytic domes and necks had solidified is most simply explained as the complementary product and risen from greater depth, as if the separation from the trachyte had been controlled by gravity. However, many other volcanic piles with similar development of trachyte, like Ascension and Saint Helena Islands, do not exhibit equivalents of the Leone lava.[3]

Chemical Contrast of Plutonic and Effusive Rocks

An effusive magma is usually richer in silica, potash, and soda, and poorer in iron oxides, lime, and magnesia than the corresponding deep-seated rock belonging to the same clan. This significant fact is illustrated in Table 1. It is explained by the special conditions at a central vent. There the fluxing gases are concentrated and so lengthen the temperature interval of crystallization. Moreover, this interval is passed through not once but as many times as the volcano rhythmically changes from active to dormant. On account of their high density the early-formed compounds sink, and the upper part of the lava column becomes more salic than the original magma

[1] C. Vélain, Mission de l'île Saint-Paul, Paris, 1888, p. 181. A. Lacroix, Minéralogie de Madagascar, Paris, vol. 3, 1923, p. 229.

[2] R. A. Daly, Jour. Geol., vol. 19, 1911, p. 297. P. D. Quensel, Bull. Geol. Inst. Upsala, vol. 11, 1912, p. 288.

[3] R. A. Daly, Pub. 340, Carnegie Inst. of Washington, 1924, p. 121; Proc. Amer. Acad. Arts and Sciences, vol. 60, 1925, p. 76; *ibid.*, vol. 62, 1927, p. 70 with references. Compare also J. B. Bebiano on the Cape Verde volcanoes in Bol. 25, Agencia Geral das Colonias, Lisbon, 1927; and the many recent publications by A. Lacroix and H. S. Washington on the petrology of the oceanic islands as well as Madagascar (Lacroix).

The principle of gravitative differentiation in volcanic vents does not, of course, exclude the possibility of eruption of ultrabasic lava at main vents opening well above sea level.

would normally be if solidified under plutonic conditions. Effluent lava usually comes from the upper levels of the column, where, too, any "gaseous transfer" would tend to concentrate salic material. Thus the general chemical relation of plutonic and extrusive in each clan seems to afford additional evidence of density control in differentiation.

Primary Banding

Sharply marked layers of contrasted materials in some plutonic bodies are evidently products of differentiation. Among the many examples are those found in the gabbros and peridotites of the Scottish islands Rum and Skye, the diabase of the Nordingrå region, Sweden, the gabbro of Cape Neddick, Maine, the gabbro of the Duluth lopolith, and a considerable number of strongly alkaline masses, such as the nephelite syenites of Ontario.

The gabbroid bands of Skye and Rum are composed of varying proportions of feldspar, pyroxene, and iron ore, the rocks tending to approach anorthosite at one extreme and iron-rich pyroxenite at the other. The banding of the Skye peridotite is analogous. After a careful study Harker concluded that all these bands represent materials differentiated at depth and later, as a heterogeneous assemblage of contrasted liquids, erupted and crystallized at the visible levels. The anorthite and olivine molecules of the allivalitic and peridotitic bands of Rum are described as having "a decided mutual repulsion." Harker offers no explanation of the assumed differentiation in depth, regarding the question as hopelessly speculative.[1]

Other petrologists believe the layering in similar bodies to have been caused by differentiation in place. Ussing explained the hundred "kakortokitic" bands of the Greenland Ilimausak intrusion by fractional crystallization and separation under gravity and specifically rejected the hypothesis of successive intrusions.[2] In order to account for the layering of the Duluth lopolith, Bowen relies on the sinking of its floor during the crystallization of the body. The consequent warping of the solidifying mass is supposed to have brought into play the principle of the filter press. Thereby a layer composed of crystals is compacted by the squeezing-out of the residual liquid, which itself goes to form an adjacent parallel layer, also finally solidified. "Constant repetition of this action as cooling and warping proceed should

[1] A. Harker, Geology of the Small Isles, Memoir Geol. Survey Scotland, 1908, p. 69; The Tertiary Igneous Rocks of Skye, Memoir Geol. Survey United Kingdom, 1904, pp. 90, 117; The Natural History of Igneous Rocks, New York, 1909, pp. 138, 240, 341.

[2] N. V. Ussing, Medd. om Grönland, vol. 38, 1911, p. 355.

produce innumerable bands such as those seen in the Duluth mass."[1]

Wandke appeals to "the pulsatory escape of mineralizer" as "the mechanism responsible for the banding" in the Cape Neddick gabbro. The rhythmical escape of the volatile components is assumed to be accompanied by local changes of pressure. This idea is thus somewhat similar to that favored by Ussing for the Ilimausak case.[2]

Wagner accepted crystal fractionation under gravity as one of two principal conditions for the development of the extraordinary banding in the Bushveld norite. The other condition is "an intermittently recurring rise of the isogeotherms due to the spasmodic subsidence of the floor" of the noritic body, which, like the Duluth gabbro, is strongly basined. One may well question that the internal heat of the earth could sufficiently affect the temperature of the norite before that mass, huge as it is, was completely solidified.[3]

The obscurity of the problem is illustrated in the basic member of the Bushveld Complex. The relatively low position of the banded phase within its noritic lopolith seems to indicate gravitative control, the early-formed crystals having settled down at different rates, according to their density and size. But the main difficulty is to account for the *repetition* of the process, so that several layers of each nearly monomineralic type, anorthosite, pyroxenite, or chromitite, were formed in varied alternation.

[1] N. L. Bowen, Jour. Geol., vol. 27, 1919, p. 418. Bowen (The Evolution of the Igneous Rocks, Princeton, 1928, p. 168) has offered a partly analogous suggestion regarding the banding of the Bushveld norite. Again he assumes deformation of the crystallizing magma. "The action is of the nature of the intrusion of the more completely liquid portions into rifts in the crystal mesh of the part of the mass in which the proportion of crystals is much greater. The process is thus a sort of auto-intrusion. Further crystallization-differentiation by gravity in the liquid layers thus intruded may give extreme effects, for this liquid virtually begins its crystallization anew under conditions that are ideal for producing such effects."

W. H. Goodchild (Mining Mag., 1918, sep. p. 69) favors the hypothesis that, under suitable conditions, anorthosite has been formed by the hydrolysis of pyroxene.

[2] A. Wandke, Amer. Jour. Science, vol. 4, 1922, p. 300.

[3] P. A. Wagner, Mem. 21, Geol. Survey Union of South Africa, 1924, p. 80.

While this book was going through the press, the splendid monograph by A. L. Hall on the Bushveld Igneous Complex (Mem. 28, Geol. Survey South Africa, 1932) was published. In this, one of the masterpieces of petrology, the reader will find details regarding the banded character of what Hall has named the "critical zone" and also regarding the beds of magnetite at higher levels in the Complex.

Still more recently J. W. Peoples (Abstracts of papers read at the 1932 meeting of the Geological Society of America, p. 73) has briefly described a remarkable parallel to the Bushveld banding in a large basic intrusion of the Beartooth Mountains, Montana.

Since the norite was some kilometers in thickness, thermal convection (depending on the fourth power of the thickness of the liquid body) might be theoretically regarded as a condition. Thus, after a crop of plagioclases, pyroxenes, and oxides had sunken from the upper, cooled part of the noritic melt, a convective overturn of the remaining liquid would result in a new chilling above and the sinking of a second crop of crystals. A number of such overturns and showering of crystals might conceivably have given the observed banding[1]. Such a rhythmical process is of duration necessarily limited, because the density gradient in the liquid, due to differential cooling, is at least partly annulled by incipient crystallization, the residual liquid becoming less dense than the original noritic liquid at the same temperature.[2]

A second possibility emerges from the fact that the norite was slowly basined during its crystallization. Along any fixed vertical line in a liquid mass so disturbed, the temperature would vary more or less rhythmically, with a resulting rhythmical showering of early-formed crystals and, as before, development of banding in depth.

We may also consider the effect of reaction of the original liquid with numerous xenoliths. At each of these sedimentary contacts the reactions, obeying the rule so clearly stated by Bowen, accelerated the precipitation of early-formed crystals. The character and abundance of the precipitates would depend upon the size and composition of the xenoliths, and the showering of the crystals at a given vertical line would vary with motion of the xenoliths as these passively shared in the basining of the complex.

Perhaps a combination of thermal convection and reactive crystallization with the sinking of crystals gives a more plausible explanation. In any case, shearing of the mass, as its basin structure was slowly completed, would tend to sharpen contacts among the bands.[3]

[1] The plagioclase is supposed, frankly without experimental proof, to have been denser than the molten norite. In accord with this view are several passages in N. L. Bowen's "The Evolution of the Igneous Rocks" (pp. 138, 141, 145, 158, 161, and 168). L. L. Fermor (Rec. Geol. Survey India, vol. 58, 1925, p. 197) has made detailed study of many flows of the Deccan trap and concludes that crystals of labradorite as well as olivine did sink in some of the flows.

According to S. Foslie (Jour. Geol., vol. 29, 1921, p. 713), the olivine crystals of the Raana norite accumulated in bands not because of differential density but through the operation of "convection currents and other movements of the magma."

[2] F. F. Grout (Jour. Geol., vol. 26, 1918, pp. 457, 639, 641) tried to explain the banding of the Duluth lopolith by postulating convection of a kind too special to be satisfactory to the physicist.

[3] Another big body showing bands analogous to those in the Bushveld mass is the Sierra Leone gabbro-norite. There, according to N. R. Junner (Compte

Conclusion. Genetic Classification of Magmas and Rocks

A review of the subject shows wide divergence of opinion about the mechanism of magmatic differentiation. A principal reason is lack of agreement regarding the nature of the material differentiated to form the actual rocks. Some petrologists of a generation ago assumed it to be a primary magma of composition between granite and basalt. Loewinson-Lessing assumes two primary magmas, the granitic and basaltic, which are capable of dissolving each other and also the heterogeneous rocks of the earth's crust. According to Harker, the material is a primary basic melt initially bearing crystals of early formation. Bowen takes it to be more or less completely molten basalt.

The contrasts of these and other views are possible because of the baffling problem of the earth's interior. Until a theory of the planet's constitution and dynamic habit is generally accepted, consensus of opinion must be delayed. To attempt such a theory is an arduous task, and yet the petrologist can hardly escape it if he is serious about his job.[1]

The theory of the earth outlined in this book permits, if it does not enforce, belief in the large development of secondary magmas within and just beneath the earth's crust. Considering the heat required, some petrologists believe this to be an "extreme" view. Among visible eruptives the thermal needs are at maximum for the batholiths. The batholiths themselves are "extreme" bodies and require an extreme interpretation. Nothing could be more extreme than to assume, without more evidence than is likely to be forthcoming, their emplacement by pure injection and to explain their chemistry by pure, direct crystal fractionation. Progress in this difficult field of natural history demands thinking to scale, particularly thinking to an earth scale.

As far as post-Archean silicate melts are concerned, spontaneous unmixing of liquid phases seems to be doubtful. Pure molecular diffusion is clearly inadequate as a differentiating mechanism of importance. Gravitative separation has been emphasized as the

Rendu, Cong. Géol. Internat., South Africa, vol 2, 1930, p. 417), the bands consist of troctolite, anorthosite, ilmenite, and titanomagnetite, with which are associated the dominant lenticular units of gabbro and norite. Junner regards the body as a "large basin-shaped sheet."

[1] L. Milch (Geol. Rundschau, vol. 15, 1923, p. 338) objected to any *Universalhypothese* in petrology on account of its necessarily "subjective" character. But can any advance be made in our science without subjective approach to its endless array of facts? Milch himself favored a *Universalhypothese* when he explained igneous rocks as derivatives of a magma zone which is stratified and yet schlieric in its upper parts.

leading process. Crystal fractionation under gravity as well as by filter pressing is a demonstrated process, but perhaps to be ranked no higher in efficiency than the self-cleansing of basalt, either contaminated or temporarily inclosing the products of pure melting. Additional facts supporting the last statement will be noted in Part III.

Serving as a skeleton summary of the earlier chapters and also the theoretical conclusions of Part III, the following genetic classification of magmas and rocks is appended (Table 41).[1]

TABLE 41.—GENETIC CLASSIFICATION OF MAGMAS IN THEORY

Magma	Representative Rocks
1. Primary basaltic	Plateau basalt, many diabases, gabbros
2. Primary Sialic	Primitive felsic rocks, complementary to the basaltic substratum
3. Anatectic-granitic	Many early Pre-Cambrian granites, pegmatites, aplites
4. Direct differentiates of primary basalt.	Some peridotites, iron ores, sulphide ores; anorthosites
5. Pure melts of crust rocks at depth	Some granites, granodiorites, etc
6. Products of gas fluxing	Some lavas at volcanoes of the central type
7. Differentiates of pure melts	Some granites, granodiorites, etc.
8. Hybrids of basaltic liquid with:	
A. Sialic crystalline rocks	Some bodies of intermediate composition
B. Sediments	Hybrid types
C. Sediments and Sialic crystallines	Hybrid types
9. Differentiates of hybrids, Class A	Some granites, etc.
10. Differentiates of hybrids, Class B.	Some abnormal granites; some feldspathoidal rocks; etc.
11. Differentiates of hybrids, Class C	Some syenites, etc.
12. Hybrids with magmas more acid than basalt	Types analogous to those under 8
13. Differentiates of Class 12.	Types analogous to those under 9 to 11
14. Transition magma marking incomplete differentiation	Intermediate types in part
15. Mixtures of two or more liquids of Classes 1 to 13	?

[1] Near the close of Chapter XXI will be found a note on a possibility emphasized by A. Holmes, namely, that we have to reckon with the occasional invasion of the earth's crust by primary peridotitic magma. As indicated there and in Chapter XXII, this idea should be seriously examined by the profession. If future investigation confirms it, such a table as No. 41 would need extension. However, field geology clearly points to the rarity of such possible peridotitic invasions and to the normal, much greater importance of primary basaltic magma in petrogenesis.

CHAPTER XV

MECHANISM OF VOLCANIC VENTS OF THE CENTRAL TYPE

INTRODUCTION

The larger part of volcanological literature deals with the activities at cone and crater. Few handbooks treat of all the essential problems of central eruption; yet any general theory of igneous action must undergo the test of such a thorough questionnaire. So it is with the hypothesis that post-Archean volcanism is the direct or indirect result of abyssal injection from the basaltic substratum. The leading questions affecting central eruptions relate to:

1. The localization and opening of the vent.
2. The persistence of activity at intervals through thousands of years.
3. The intermittent character itself, expressed in (*a*) the alternation of active and dormant phases and (*b*) the pulsatory or geyser-like quality of eruption during the active stage.
4. The origin of the heat, which by radiation at active craters is lost in enormous quantities.
5. The usual evolution of a vent as illustrated in degree of explosiveness and, it may be, in the nature of the lava emitted.[1]

The present chapter is occupied with these questions, certain aspects of which were considered in an earlier publication but need review in the light of the remarkable series of data secured during the last two decades. By personal observation and by giving hospitality in the field to other experts, Jaggar, Perret, and Friedlaender have illustrated the rich results that come from permanent observatories at strategic points. These leaders in earth science have amply shown the need of full support for, and multiplication of, such stations as those at Kilauea, Saint Pierre, Naples, and Lassen Peak.

SOME DIRECT CONSEQUENCES OF ABYSSAL INJECTION

The estimate of 60 kilometers for the average depth of the surface of the substratum below the continents may not be exact, but it

[1] The author's original discussion of the subject will be found in Proc. Amer. Acad. Arts and Sciences, vol. 47, 1911, pp. 67–108 and 119–122.

serves as a numerical basis for the statement of some immediate effects of injection.

First, the general hypothesis supplies reasons for the ascent of basaltic magma to the earth's surface (see page 247).

Second, the assumed abyssal injections vary greatly in width (volume), total thermal energy, and length of life as magma. Hence they differ also in their capacity for differentiation, as well as in power to stope and otherwise incorporate country rocks.

Third, the juvenile gases of magma, forced from the substratum level to levels where the pressure is 15,000 or more atmospheres smaller, are probably out of chemical equilibrium with one another and by new combinations give a furnace effect. They diffuse upward and tend to supersaturate the liquid. The concentration of gas in the upper part of the lava column is further ensured if the column is stirred by vertical currents, the diving lava having left its excess gas at the place of least pressure. Some vesiculation of lava columns feeding central vents is an observed fact.

Fourth, resurgent gases, that is, volatiles entering the basaltic liquid from xenolith or wall rock, may cooperate in opening vents of the central type, but the incorporation of these foreign materials demands a net expenditure of thermal energy—hence some "damping of the fires." On the other hand, juvenile gas, if emanating in sufficient quantity, may open the vent and keep it open for a long period of time.

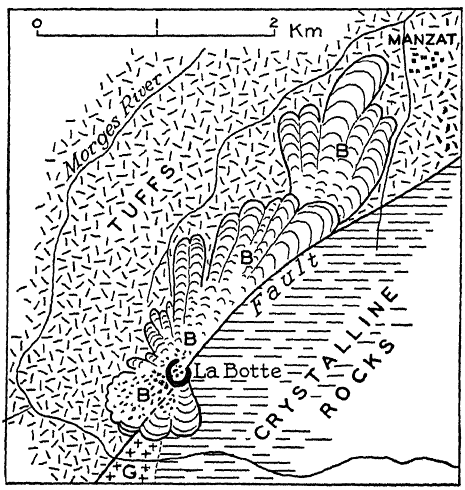

FIG. 116.—Map of the volcano of La Botte, Central France, illustrating extrusion at a fault line. *B*. effusive basalt; *G*, granite. (*G. Garde*, *Bull. soc. géol. France*, 1922, *p.* 291.)

LOCALIZATION AND OPENING OF THE VENT

Enlarged Fissures.—The events of 1783 at the famous Laki fissure of Iceland illustrate the close relation between some central eruptions and fractures of the crust. For much or all of its length the erupting fissure was probably connected with a typical narrow abyssal injection, though the connection may have been indirect. Many hills of the cone-and-crater type were built along the Icelandic crack, which emitted a flood of basalt on a scale without rival in

human history.[1] A similar bond between central vent and fissure is illustrated with diagrammatic clearness in the Auvergne (Fig. 116). Analogies are found in the lines of cones built along the lateral cracks

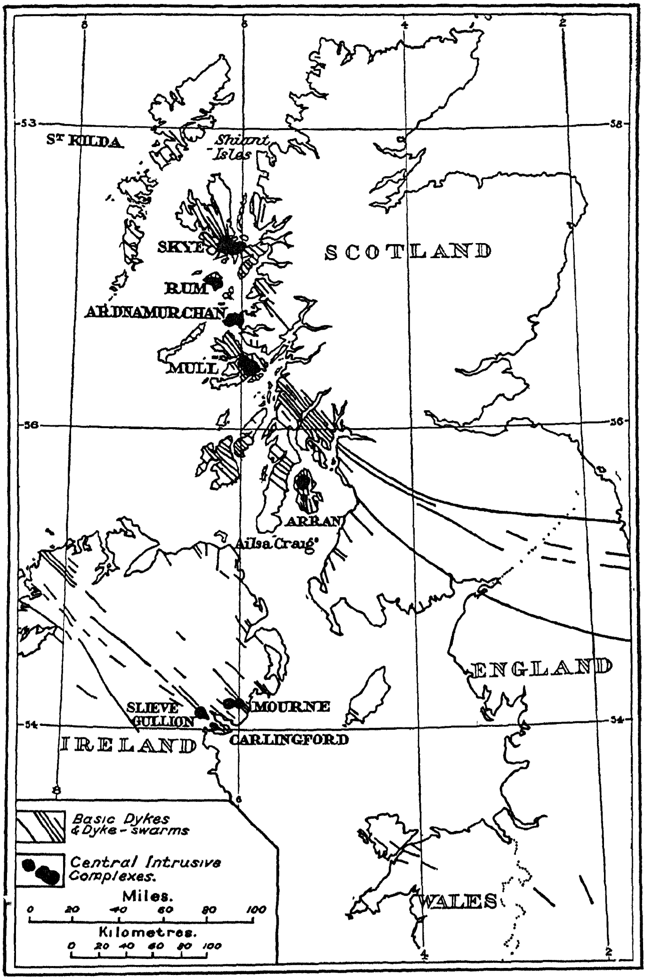

FIG. 117.—Location of Tertiary central intrusive complexes of the British Isles, and relation to systems of Tertiary basic dikes. (*Ardnamurchan memoir, Geol. Survey Scotland*, 1930, *p.* 53.)

of Mauna Loa, Etna, and other major volcanoes; according to Dutton, in the alined necks of the Mount Taylor district, New Mexico; and apparently in the central vents of the Scottish Western Isles (Fig.

[1] Specially graphic is Helland's map of the cones along the Laki fissure, a copy of which appears in E. Suess, La face de la terre (translated by E. de Margerie), Paris, vol. 3, 1918, p. 1537.

117). One or more *points* on each line of fracture were favored in the eruptivity, while the rest of the fissure was either not opened clear to the surface at all or else was rapidly sealed by freezing of the lava.

Since erupting fissures are seldom more than a few meters wide at the surface, each has been widened where it carries cone and crater of prolonged activity. This may depend upon one or more of four different factors: solution and mechanical removal of wall rock by emanating lavas; melting and explosive abrasion by magmatic gas emitted through the column of lava. The relative efficiency of these processes will be considered later, in connection with the problem of the persistence of eruption.

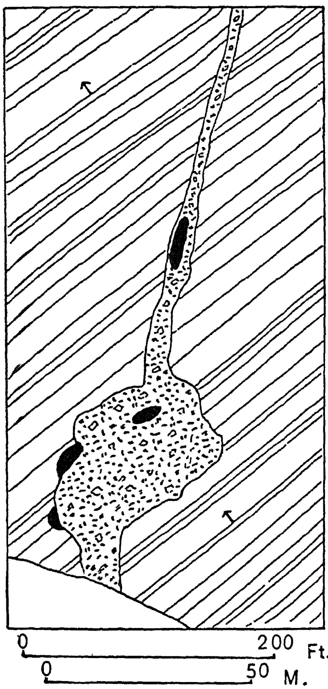

FIG. 118.—Diatreme opened on a fissure, Laws Castle, Fifeshire. *Lined area,* Carboniferous sediments; dip indicated. *Dots,* agglomerate of sediments, lapilli, basalt; *solid black,* basalt. (*After A. Geikie, Geology of Eastern Fife, Glasgow,* 1902, *p.* 218.)

A fissure may be too narrow to permit the rise of gas free from magma and yet wide enough to give passage to hot juvenile gas. Rising at one point, the gas may flux the wall rock, enlarging the opening which becomes locally a vertical pipe with or without a crater of explosion at the surface. The original fissure may not be discernible by the geologist.

Diatremes.—A vertical pipe opened by pure explosion is a diatreme, which may or may not be located on a visible fissure (Fig. 118). It may, of course, be enlarged or otherwise changed by volcanic action of a different kind. By artificial explosions Daubrée drilled, through slabs of granite, holes analogous to diatremes.[1]

Plutonic Cupolas.—Lastly, the localization and partial boring of some central vents have been natural incidents of batholithic invasion of the earth's crust. The rise of batholithic magma is differential. Partly because of gas control its attack on the roof is most efficient at points, rather than along lines or large areas (Fig. 119). Hence round bosses or small stocks are characteristic cupola ornaments of batholiths. With their steep surfaces of contact, general shape, and crosscutting relations, some bosses closely simulate volcanic necks.

[1] A. Daubrée, Bull. soc. géol. France, vol. 19, 1891, p. 317.

Evidently a cupola increases as well as localizes the likelihood of true volcanic action. Its own thin roof may be punctured by blowpiping fusion or by pure explosion. The resulting vent is, then, of composite origin. The upper part resembles one or other of the two types of central vents already described; the lower part is the result of all the agencies of plutonic replacement of crust rock.

Stoping may continue even after explosion has bared a cupola magma to the sky. Thus, according to R. T. Walker (personal

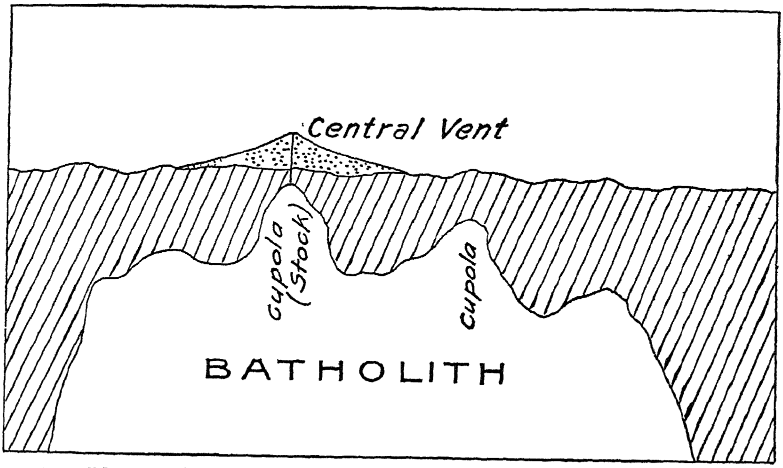

FIG. 119.—Ideal section showing formation of volcanic vent through the differential rise of replacing magma.

communication), a number of small plutonic stocks in the region of Bingham Canyon, Utah, are connected with breccia-filled volcanic vents in such fashion as to suggest that the stocks were enlarged by downstoping some of the breccia.

A number of vents may be opened above a single batholith. They will not have equally long lives, for a more favored vent draws the juvenile gases away from the others (Fig. 119).

Continuance of Activity at Central Vents

Many vents have been intermittently open for hundreds of thousands of years. The examples of Etna and the Miocene-Pliocene Cantal volcano (Fig. 120) may be recalled. Prolonged activity at a point, whether continuous or intermittent, depends upon *victory in the struggle with cold.* How is the victory attained? How is the heat of the underlying magma chamber transferred to the narrow pipe? Hawaiian vents supply data on this fundamental question. Though Kilauea may be the vent of a satellitic injection, its thermal mechanism

is doubtless of the same kind as that ruling a volcano fed from a main abyssal injection (Plate III).

Loss of Heat at Kilauea.—A rough idea of the high rate at which heat is given off at the active Kilauea may be obtained (Fig. 121). Siegl has supplied a required datum. The general equation is

$$\log S = \log c + n \log T,$$

where S is the number of calories radiated per second per square centimeter; T, the absolute temperature of the lava, in degrees centigrade;

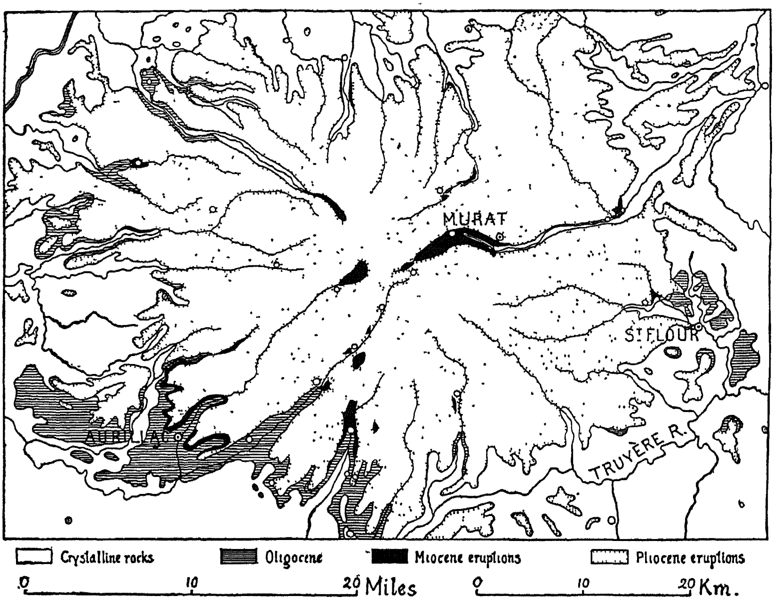

FIG. 120.—Map showing the long continuance of volcanic action at the Cantal, France. The eruptions occupied part of Pliocene and Miocene time. (*After M. Boule, Bull. serv. carte géol. France, No.* 76, 1900, *p.* 29.)

and c and n are constants. For basalt, Siegl found $c = 0.589 \times 10^{-12}$ and $n = 4.083$.[1] His experiments show that the equation holds for basalt up to 472° Abs. Extrapolation on Siegl's curve can, of course, give only approximate values of S at higher temperatures, but their order of magnitude, thus inferred, is stated in column 3 of Table 42. That the extrapolation involves no large error of principle is shown by comparing Vogt's time curves for the cooling of various slags, while allowance is made for the rise of the specific heat with temperature.[2]

In 1909, the author used a Féry pyrometer to measure the average temperature of the non-incandescent scum which regularly covered

[1] K. Siegl, Sitzungsber. Akad. Wiss. Vienna, math.-nat. Kl., vol. 116, 1907, p. 1203.

[2] J. H. Vogt, Skrifter Videns.-selsk. Christiania (Oslo), Kl. I, 1904, No. 1, p. 50.

TABLE 42.—RATES OF RADIATION OF HEAT FROM BASALT

t°C.	T° Abs.	S
450	723	0.28
727	1000	1 04
1000	1273	2.80
1200	1473	5 07

at least two-thirds of the lava lake at Kilauea. The average temperature of this part was estimated at about 450°. The corresponding

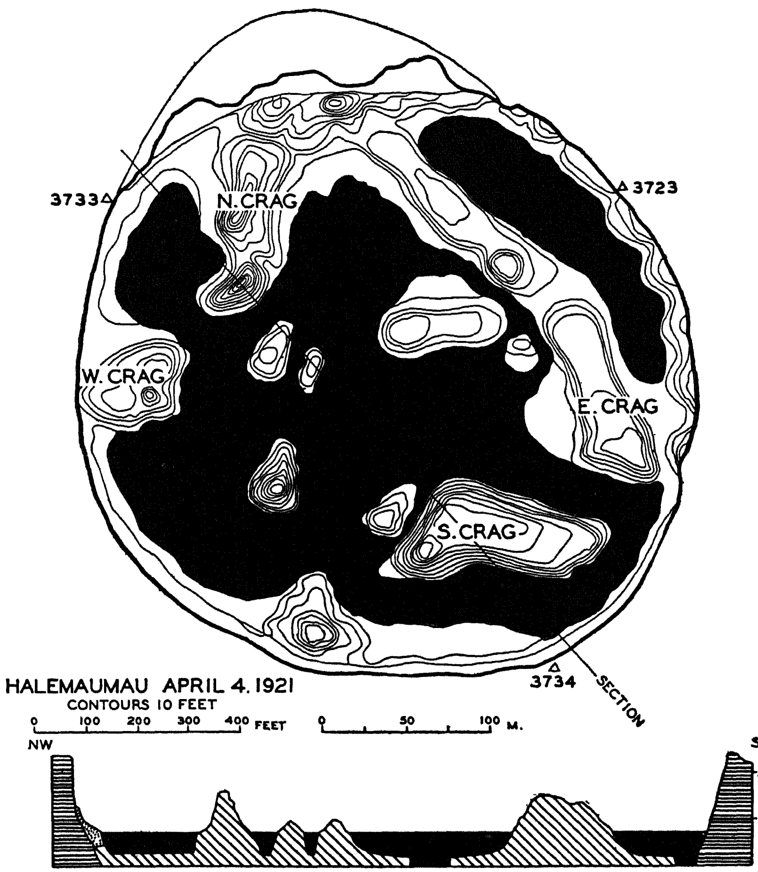

FIG. 121.—Map and section of the lava lake at Kilauea, Apr. 4, 1921. Liquid lava, *black.* Bench lava shaded, in section; *blank*, in map. Shore walls veneered with new lava, left after subsidence of the lava column. Contour interval, 10 feet. Elevations of triangulation points given in feet. (*From T. A. Jaggar, Mon. Bull. Hawaiian Volcano Observatory, vol.* 9, *No.* 4, 1921.)

loss of heat may be taken as about 0.25 calory per square centimeter per second.

No area of the hottest lava sufficed to cover the "black spot" of the pyrometer long enough to give the temperature. However, the behavior of the galvanometer needle during the brief exposures to the hot lava in the "Old Faithful" fountains showed that its temperature was well above 1000°. From the color the temperature of the hottest lava visible in the lake was estimated to be not far from 1200°—a value close to that accurately measured (1185°) by Day and Shepherd for Kilauea lava in 1912.[1] The third of the lake relatively free from scum had an average temperature of about 1000°C., corresponding to a loss of heat equal to about 2 calories per square centimeter per second. Compare Plate III and also Plate II.

With radius of 100 meters a circular lake of the kind would lose heat at the approximate rate of 300,000,000 calories per second. The actual lake of 1909 probably lost more than 300,000,000 calories per second, a rate at least fifty times faster than the rate of loss of heat by conduction into the walls of the Kilauean pipe, even if the pipe be assumed to have a radius as great as 100 meters and a depth of 2000 meters.[2] A contrast of the same order may be expected in the case of any strongly active volcano.

According to rough calculation, the heat radiated at Kilauea between 1907 and 1920 could be supplied by the cooling of 20 cubic kilometers of magma through a range of about 100°.

Methods of Transfer of Heat.—Heat is brought to the top of a volcanic pipe (1) by explosive removal of material, followed by rise of lava from the still liquid chamber, (2) by simple overflow of lava at the lip of the crater, (3) conceivably by rise of lava and its effluent discharge, not under the open air but into cavities or along covered channels just below the level of the floor of the crater, (4) conceivably by thermal convection, (5) by the upward passage of juvenile gas, and (6) by circulation of the lava in the vent, enforced by local decrease of density where clouds of gas bubbles form, and also through the increase of density undergone by the liquid that loses gas at the crater—a compound process described as "two-phase convection."

1 and 2. The first two processes have played no essential part in keeping up the supply of heat at Kilauea since 1823, when detailed records of its activity began.[3]

[1] A. L. Day and E. S. Shepherd, Bull. Geol. Soc. America, vol. 24, 1913, p. 601.

[2] See "Igneous Rocks and Their Origin," pp. 255–258.

[3] At the Hawaiian vents, violent explosion is seen to be a subsidiary, quite unessential condition for volcanic action, even in the narrow sense of referring merely to volcanoes of the central type. Just as clearly the phenomena of fissure eruption (plateau basalts) show that volcanism proper does not necessarily imply explosive violence.

3. Shepherd has outlined the third hypothesis, with approval in the case of Kilauea, which he regards as "merely a lava spring with not one but many irregular subterranean outlets . . . in the porous structure of the Hawaiian range."[1] There are several serious objections to this view.

By hypothesis the effluent channels must be situated near the lake level; yet, after the sinking of the lava before July, 1909, and again after the much greater withdrawal of liquid in 1924, the crater walls showed no sign of the existence of such channels. Nor can one assume offhand that even those dikes that have been exposed by the erosion of cones originally 1000 to 4000 meters in height were effluent channels operating when these long-lived volcanoes were active. The "porosity" of a basaltic cone is not of the kind permitting the steady subterranean outflow of lava from the region of the crater during several successive years. The quick chilling of the supposedly interfluent lava, in fissure or old lava tunnel, could not fail to seal that channel speedily. The wall of the crater and its main channel of supply must, therefore, be made practically impervious to lava except as fissures were opened from time to time. Such intermittent fissuring would permit the withdrawal of the excess lava, but during the intervals between the fissurings the lava should rise at the crater, if Shepherd's hypothesis were true. The fact is that the lake level at Kilauea has remained nearly constant for months together.

Further, the walls of visible channels where the Kilauea lava circulates tend to be glazed and, like the remarkable empty pipe at the top of Hualalai volcano in the same island, made "airtight" by the heat.[2] This seems reasonable on *a priori* grounds and also represents a difficulty with the idea of feeders in the form of "wide-spreading branches below."

Still another is the behavior of the Kilauea lava when its withdrawal is rapid. Repeatedly its movement has then been "like liquid pouring into a funnel, or like the waters swirling out of a bath tub after the plug is drawn."[3] That description exactly matches one given verbally by J. A. Kennedy, then president of the Inter-Island Steamship Company, who with a friend witnessed the disappearance of the lava in 1908. A later instance is recounted by Jaggar.[4] Can there be any doubt that the Kilauea vent, below the superficial mass of lava lake and talus, was in reality an "unimpeded" pipe, normally filled with

[1] E. S. Shepherd, Bull. 61, Nat. Research Council, Washington, 1927, p. 262.

[2] T. A. Jaggar, Bull. Seism. Soc. America, vol. 10, 1920, p. 164.

[3] G. H. Fairchild in C. H. Hitchcock, Hawaii and Its Volcanoes, Honolulu, 1909, p. 254.

[4] T. A. Jaggar, Amer. Jour. Science, vol. 44, 1917, p. 173.

lava? For years before and immediately after 1909 this pipe, the site of the "Old Faithful" of the time, seems to have been the main channel of circulation, if not the only one, and its diameter at the top was little more than 20 meters.

For these and other reasons, then, this third hypothesis seems not to account for Kilauea or for the prolonged activity of other vents of the central type.

4. Thermal convection alone cannot be essential in postponing the solidification of a column of lava. If the convection be lively enough to keep the column molten, the thermal gradient must be low. But the coefficient of thermal expansion is small, and the viscosity is considerable at depth. Moreover, the narrowness of a volcanic pipe

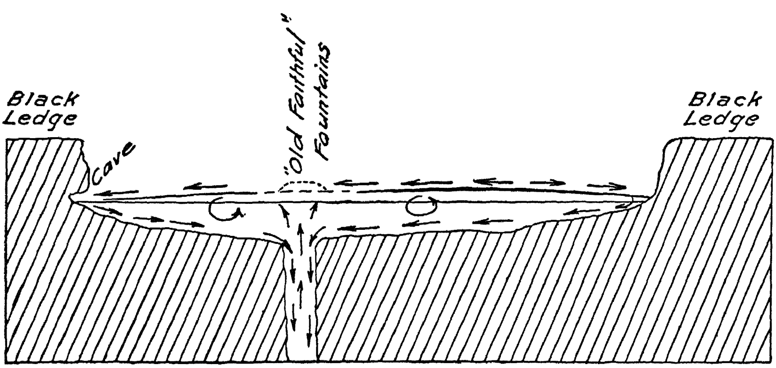

FIG. 122.—Section of Halemaumau illustrating two-phase convection.

introduces notable boundary effects, further inhibiting convection; the conditions are here different from those of sill, laccolith, or batholith with great horizontal extension. Thus the low working potential and the resistances to be overcome conspire to make thermal convection in the pipe incomparably less rapid than in an artificial water system. Clearly this process could not keep the temperature of the Hawaiian lake at anything like the observed value. On the average, each square centimeter of its surface radiated, in 1909, about 1 calory per second or 86,400 calories per day. Taking 0.35 as the mean specific heat of the lava, this implies a daily loss of heat equal to that suffered by a column of basalt with cross section of 1 square centimeter and height of more than 2400 meters, as this column cools 100°. It is manifest that more effective agencies have been at work, to keep Kilauea active, year in and year out.

5. The lava of the Hawaiian lakes has always been foamlike. The bubbles of gas that make up so much of its volume have risen some distance through each lava column. If they originated at great depth,

they have brought their thermal energy with them and thus helped to prolong activity. The method will be considered in the next section.

6. When the Kilauea lake was fully active, it exhibited a constant, very powerful kind of convection (Fig. 122). In 1909, this suggested to the author a new explanation of the activity—at least in part. The persistent streaming of the lava into grottoes or caves, characteristically developed at the shore cliffs of the lake, was evidently due to deleveling of the lava at the surface. In general, the "scum" or thin crust at the central part of the lake stood higher than that over the channels leading to the caves. The scum prevented or retarded the escape of the magmatic gases, which, therefore, accumulated beneath it and formed a froth or emulsion of liquid and gas, relatively low in density.[1] Thus the crust was raised in one or more areas. At each cave, because of reflection from its roof and because of special heating by the actual combustion of sulphur, hydrogen, and other gases, the crust was rapidly and completely fused. The escape of the gases was facilitated and the surface of the lava in the cave correspondingly lowered. The surface slopes were steepest in the channels leading to the caves, and there streaming at estimated rates of 2 to 5 kilometers per hour was observed. Elsewhere the surface slopes were lower and streaming was less rapid. The caves were not outletting tunnels, as had often been stated, but each, like others that were higher up in the walls and hence accessible, was closed at the distance of a few meters from its entrance; the inner part of the wall had simply been melted back. The lava that streamed as a superficial current into the cave returned to the main part of the lake. Only one way was open. Having lost its dilating gas, the now denser lava sank and in depth flowed back toward the center of the lake. Similarly the ever-changing slopes of the surface elsewhere compelled currents, vertical, horizontal, and vortical, of the most complex design (Fig. 122).[2]

This type of magmatic movement was named *two-phase convection*. It depends upon the presence of a liquid phase and a gas phase in the lava.

If two-phase convection prolongs the life of a volcano to an important extent, bubbles of gas must form in the lava at depths of a few kilometers, though, of course, not necessarily tens of kilometers.

[1] At many points the wall of the crater was thinly coated with black glass, representing splashes from the adjacent lake. These splashes almost instantly "froze" to the wall. The glass was extremely porous—of spongy appearance. The vesiculation was almost if not quite complete before the splash struck the wall, and it is simplest to suppose that the lava at the lake's surface was likewise a froth.

[2] One of Jaggar's excellent photographs of lava streaming into a grotto is to be found in the Volcano Letter of Mar. 26, 1931.

Whether this condition is actually met is a question as yet without final answer.

Evidence from the rocks themselves is not easy to obtain. Vesicularity does characterize some dikes, sills, and other intrusives that evidently bore rock pressures of the order of 100 atmospheres. But the vesicularity of any solid intrusive body is probably not that of the same mass when it was liquid; during the slow crystallization gas bubbles would have been squeezed out. We note also that supersaturation with gas is specially favored at volcanic pipes; in the normal intrusive magma the gases are not concentrated so much. Hence the absence of bubbles in most selvages of intrusive bodies can hardly be used as an argument against the idea of two-phase convection at central vents.

Again, the abundance of free gas in the first lava to appear at the Mokuaweoweo (Mauna Loa) vent after several years of dormancy seems to mean that bubbles actually rose from considerable depth and collected just under the solid plug of this pipe. Pure molecular diffusion is too slow to account for the foamlike quality of this early lava. The lateral eruptions of Mauna Loa are also foamlike. If, as generally believed, such effluent discharges originated at some depth below the crater, it appears reasonable to assume at that depth gas in excess and corresponding vesiculation of the lava column. The conditions leading to the catastrophic explosions of more ordinary volcanoes after prolonged dormancy are likewise worthy of investigation; how have these huge masses of gas been collected under the respective plugs?

Experiment with artificial melts has not yet solved the problem. Shepherd of the Geophysical Laboratory at Washington wrote: "A little simple arithmetic readily shows vesiculation at any great depth, or the movement of vesiculated material, to be improbable." He and his colleague Merwin remark that "we have as yet no data which allow us to determine at what depth bubbles can form or are likely to form," but they believe that Shepherd's former statement remains true. How far this judgment differs from that of a petrologist is illustrated in Erdmannsdörffer's belief that vesiculation at considerable depths is not to be doubted.[1]

Morey of the Washington laboratory has shown how greatly the gas tension rises in the residual liquid as a water-charged silicate melt crystallizes. It seems entirely possible that the crystallization of the substratum basalt and of the peripheral parts of great primary injections of magma into the earth's crust may regularly cause the super-

[1] E. S. Shepherd, Bull. 61, Nat. Research Council, Washington, 1927, p. 262. E. S. Shepherd and H. E. Merwin, Jour. Geol., vol. 35, 1927, p. 114 (footnote). O. H. Erdmannsdörffer, Die Grundlagen der Petrographie, Stuttgart, 1924, p. 72.

saturation of at least the upper part of each of these injections with gas. In fact, Day and Allen, two other colleagues of Shepherd, have published the following statement, based on Morey's discussion of the "second boiling point":

> There is evidence at Mauna Loa [a perfect homologue of Kilauea in the present connection] that the whole mountain becomes distended as the pressure develops prior to a catastrophic release; also that there is some segregation due to gravity in the great magma chamber, for outbreaks near the summit release either gas alone or a light emulsion, while outbreaks at lower levels are flows of heavy lava containing little gas.[1]

"Distension of the whole mountain" because of gas pressure is hardly conceivable unless the gas at great depth is a free phase.

Even if we assume no direct or implied inconsistency in the views of the experts at the Geophysical Laboratory, it is clear that no one has yet adequately discussed one of the crucial questions: What is the law connecting pressure and the solubility of gases in magma?

Morey found the solubility of water vapor in glasses of the H_2O-K_2SiO_3-SiO_2 system to accord closely with Henry's law, up to pressures approaching 100 atmospheres. Assuming this law to hold for the andesitic magma of Mont Pelée at higher pressures, and also assuming its equilibrium weight of gas at 1200° and 1 atmosphere to be 0.14 per cent, Shepherd calculated that the lava, saturated at the depth of 1000 meters, would have to carry 35 per cent of gas by weight.[2]

But Henry's law holds, even approximately, only for a few liquid-gas pairs already investigated. The departure becomes increasingly significant as the pressure increases, temperature remaining constant. According to Bridgman, the absorption of gas by liquids is, at very high pressures, "relatively unimportant."[3]

[1] A. L. Day and E. T. Allen, Pub. 360, Carnegie Inst. of Washington, 1925, p. 80. Allen (Jour. Franklin Inst., vol. 193, 1922, p. 56) finds a "fatal defect" in the two-phase convection hypothesis because bubbles are impossible at a depth of "tens of miles." Against this argument two points may be made. First, is it proved that supersaturation of a magma with gas, due to the principle of the retrograde boiling point at the depth of even 30 miles, is really impossible? Second, as noted in the main text above, the vesiculation demanded for two-phase convection as an important cause for the activity at a volcano like Kilauea need not by any means begin at depths as great as "tens of miles."

[2] G. W. Morey, Jour. Amer. Chem. Soc., vol. 39, 1917, p. 1185. E. S. Shepherd and H E. Merwin, Jour. Geol., vol. 25, 1927, p. 114.

[3] P. W. Bridgman, Handbuch der Experimentalen Physik, Leipzig, vol. 8, part 2, 1929, p. 400. *Cf.* H. E. Boeke and W. Eitel, Grundlagen der physikalisch-chemischen Petrographie, Berlin, 1923, pp. 311, 331.

The most telling experiments are those of Goranson of the Geophysical Laboratory at Washington. These gave the following values for the solubility of water in molten granite at 900°C.:

Pressure in Bars, Approximate Atmospheres	Average Weight of Water at Saturation, Per Cent
490	3.73
980	5.70
1940	8.21
2940	8.98
3000	8.92

Between 500 bars and 2000 bars the solubility increases nearly as the *square root* of the pressure, a rule that applies also to the solubility

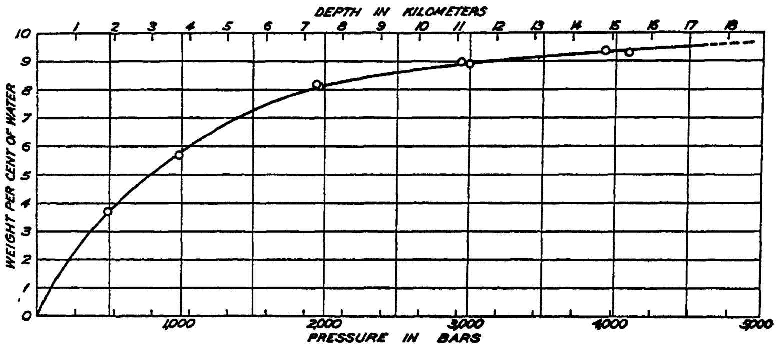

FIG. 123.—Solubility of water in granite glass, as a function of pressure within the earth at the 900° C isotherm.

of hydrogen in some molten metals, within, however, a different range of pressures. Above 2000 bars the solubility of the water increased

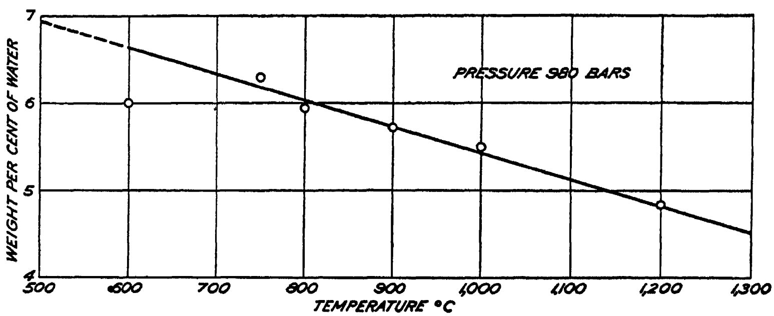

FIG. 124.—Solubility of water in granite glass, as a function of temperature at the pressure of 900 bars (metric atmospheres).

still more slowly with pressure. Goranson's pressure-solubility curve indicates at zero pressure an increase of solubility per bar of 0.0108 per cent of water. Extrapolation to 10,000 bars gives saturation at about 10 per cent of water by weight, instead of about 100 per cent as

expected if Henry's law applies (Fig. 123). Goranson further found that between 600° and 1200° the solubility of water at 980 bars showed an average decrease of 0.3 per cent for each hundred degrees of increase of temperature (Fig. 124).[1]

Other experiments are needed on the solubility of water in more basic melts, these representing the dominant magmas concerned with volcanoes of long life. Still others are needed in the case of carbon and sulphur compounds and of free sulphur itself, for vesiculation in depth may be controlled more by gases other than water, however much in excess water may be in the total analysis of volcanic gas.[2]

Until those data are in hand, we seem entitled to retain the hypothesis of gas-liquid convection as a leading cause for the stirring of magma and transfer of heat at volcanic vents. Yet there remain two distinct but related questions. Will the individual bubble of gas, on account of its low density, rise independently in the molten column? Second, will a cloudlike concentrate of bubbles tend to rise as such, shearing its way upward because of the comparatively low density of that part of the magma?

"Igneous Rocks and Their Origin" discussed the first problem at some length. The experiments of Allen had shown that small spherical bubbles, arbitrarily supposed to be of constant volume, would rise in a liquid at a terminal or steady velocity that can be computed directly by Stokes's formula for the analogous case of light solid spheres.[3] To save space, the results of certain crude calculations illustrating the use of the formulas are here omitted.

The Stokes formula (see page 278) applies if the product dxr is small compared with v. This is true for an average bubble in liquid basalt exposed to pressures greater than 200 atmospheres. The viscosity of the liquid being assumed to be only one hundred times that of water at 15°, or 1.15 in c.g.s. units, the terminal velocity of a bubble at constant volume would range between 5 and 20 meters per hour. As the bubble rises to levels of smaller pressure, it expands and naturally rises with higher speed. Since pressure increases viscosity, v for the

[1] R. W. Goranson, Amer. Jour. Science, vol. 22, 1931, p. 481.

[2] That other gases may possibly be much less soluble in magma than water is suggested by the analogy of solubilities in water itself. Thus, according to G. Just (Zeit. f. phys. Chemie, vol. 37, 1901, p. 342), the relative solubilities of four gases in water at 25° are: CO_2, 0.826; H, 0.020; N, 0.016; CO, 0.024. *Cf.* L. S. Marks, Mechanical Engineers' Handbook, 3d ed., New York, 1930, Table 16, p. 313.

[3] H. S. Allen, Phil. Mag., vol. 50, 1900, pp. 323, 519. G. G. Stokes, Trans. Cambridge Phil. Soc., vol. 9 (2), 1850, p. 8. *Cf.* C. E. Lemin, Phil. Mag., vol. 12, 1931, p. 589.

depths is doubtless much more than 1.15. Hence bubbles formed at low levels in an abyssal injection rise with extreme slowness.

We turn to the second question. Because the independent movement of single bubbles in depth is so retarded, a swarm of bubbles, formed by local crystallization (retrograde boiling) or for any other reason, is but slowly dispersed into the surrounding, less vesiculated magma and tends to remain intact. The swarm-bearing part of the magma, less dense than the rest, rises toward the crater. With the help of formulas developed by Allen (see page 279), the author has shown that a moderate amount of local vesiculation may cause the two-phase mass to rise with comparative rapidity.

Thus differential vesiculation at depth and also a mechanism by which the gas of risen magma is dissipated (as at a volcanic vent) being assumed, two-phase convection can hardly fail to stir the magmatic column, and that much more speedily than if the motion were due to purely thermal convection of the liquid. The transfer of heat may be readily conceived to supply the radiation at the crater for a long period of time.

It is important to note that two-phase convection is compelled in distinct though related ways. Stress has hitherto been laid on differential vesiculation at depth, whereby a mass of magma becomes more buoyant than the inclosing magma and rises. On the other hand, magma freed of gas at the crater tends to sink and stir the column. Even if the column is not vesiculated at all, this second cause for the vertical transfer of magma may be effective.

Perhaps also the differential concentration of gas wholly in solution at depth may initiate vertical density currents accompanying those due to the rise of free gas into the crater. Arrhenius has pointed out that normally a liquid swells a little by the absorption of the lighter gases, such as hydrogen, nitrogen, and the like. This is probably true of natural mixtures of juvenile gases with molten rock.[1] Diffusing from the feeding chamber to the base of the narrow conduit, the gases are there concentrated. In this way the magma at the lower levels of the pipe becomes less dense than the average magma and *a fortiori* less than that of the gas-freed liquid descending from the crater.

For lack of experimental data it is now impossible to estimate the efficiency of the second and third kinds of convection.

Lava Fountains.—Gas-liquid convection seems necessarily assumed if the periodic fountains of the Kilauea, Mauna Loa, Samoan, and other lava lakes are to be explained. These spectacular outbursts are

[1] See S. Arrhenius, Geol. Foren. Förh. Stockholm, vol. 22, 1900, p. 416. *Cf.* N. L. Bowen, Amer. Jour. Science, vol. 39, 1915, p. 188; and especially T. A. Jaggar, Bull. Seism. Soc. America, vol. 10, 1920, pp. 165, 168.

not generally referable to the rise and explosion of as many single, huge bubbles of gas, like those reported at Vesuvius by Perret.[1] At Kilauea each fountaining appears to have been analogous to the upspringing of a log of light wood freed at the bottom of a body of water. Through its momentum the log may jump out into the air. The lighter mixtures of liquid and bubbles are thus thought to be analogues of the wooden log.

In other part the outbursts of "Old Faithful" and similar first-rank fountains were manifestly due to true explosive dilatation of the bubbles in the "log." This was, indeed, probably the chief cause of the smaller fountains playing over the lake in 1909 or over its ancestors, Dana Lake and New Lake, nearly half a century ago. The draining of these lakes showed each to be saucer-shaped and shallow except at the narrow feeding pipes (see Figs. 121, 122). Elsewhere the depth was much too small to permit magmatic "logs" to leap to the heights actually observed, even for these minor fountains.

The periodicity of "Old Faithful" was suggestively like the rhythmical, pulsatory action so often observed when a liquid flows against friction, as water does in a drainpipe. Chiefly at this point the juvenile gases seemed to rise in two-phase mixture with liquid lava. As each more or less dome-shaped fountain sank back, it carried with it many of the included gas bubbles. Finding its proper level, the magma ran under the semi-solid or solid "scum" round about. There the gas was slowly freed and accumulated beneath the scum until the tension caused a minor explosion and one of the smaller fountains.

A major volcanic explosion, caused by the adiabatic explosion of gas, means a great amount of work done at the expense of the thermal energy of the gas and a net cooling of the system, provided the ejected material is thrown outside the crater. At Kilauea explosion of that intensity is practically negligible, so that any cooling from adiabatic expansion of gas bubbles must be small and largely dependent upon the fact that most of the volcanic gases are not "perfect" gases. In some degree the active life of Kilauea or Mokuaweoweo has doubtless been prolonged by the emanation of gas, moving independently upward through the lava column. Yet there, as at Matavanu, Savaii,

[1] F. A. Perret, Pub. 339, Carnegie Inst. of Washington, 1924, p. 75. T. A. Jaggar agrees that the Kilauean fountaining is normally due not to single bubbles of gigantic size but to swarms of bubbles (Amer. Jour. Science, vol. 44, 1917, p. 196). Besides being a mine of information regarding all other phases of Hawaiian volcanism, the collected publications by Jaggar contain many beautiful photographs of Kilauean lava fountains, fountains spinning Pele's hair, and similarly romping lavas at spectacular eruptions from the sides of Mauna Loa. Some of the

at Stromboli, at Vesuvius, and at many other central volcanoes, an important cause, if not the dominating cause, for long-continued activity is probably to be found in two-phase convection.

The Volcanic Furnace.—The heat given forth at a volcanic crater is largely due to the initial temperature of the abyssal injection which feeds the actual pipe. It may well be questioned, however, that all the emanating heat is primary in this sense. New chemical energy is likely to be provided when magma is lifted from a depth where the pressure is 17,000 or more atmospheres to levels where the pressures are only a few atmospheres and where contact with the air is estab-

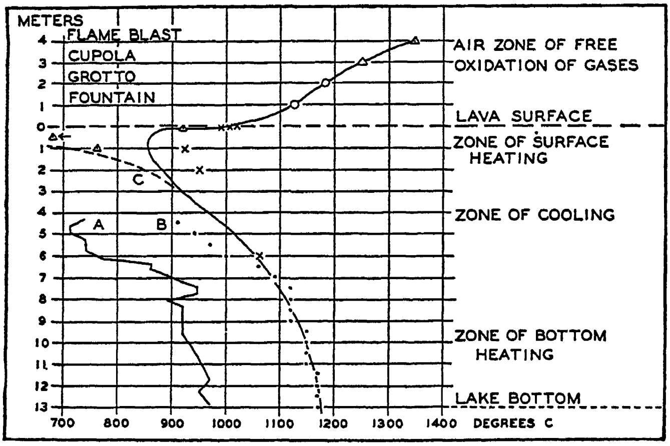

FIG. 125.—Thermal gradient of the Kilauea lava lake. Triangles, circles, crosses, and dots mean different series of measurements with Seger cones. *A*, actual uncorrected readings in large steel pipe; *B*, corrected gradient of lower lake; *C*, gradient to crusted surface of the lake. (*After T. A. Jaggar, Jour. Washington Acad. Sci*, *vol.* 7, 1917, *p.* 397.)

lished. In 1911, the author emphasized three possible modes in which a volcano may act as a true furnace, fired by chemical reactions.

1. Two years before, the author had witnessed the very high temperature developed at the shore caves of the Kilauea lava lake by actual combustion of the emanating gases with the air of the caves. Flames were observed, rising from the general surface of the lake, and this evidence of true combustion has become familiar to Jaggar, Perret, and other experienced observers of active lava.

most instructive of these unique views are published in the Bulletins of the Volcano Observatory and in the American Journal of Science. Other similarly superb photographs and significant discussions of Hawaiian volcanism are due to F. A. Perret (Amer. Jour. Science, vol. 35, 1913, pp. 139, 273, 337, 469, 611, and vol. 36, 1913, pp. 151, 475).

Jaggar has suggested a special, analogous cause for the generation of heat at the Kilauea lake of lava, when active. The crusts, constantly

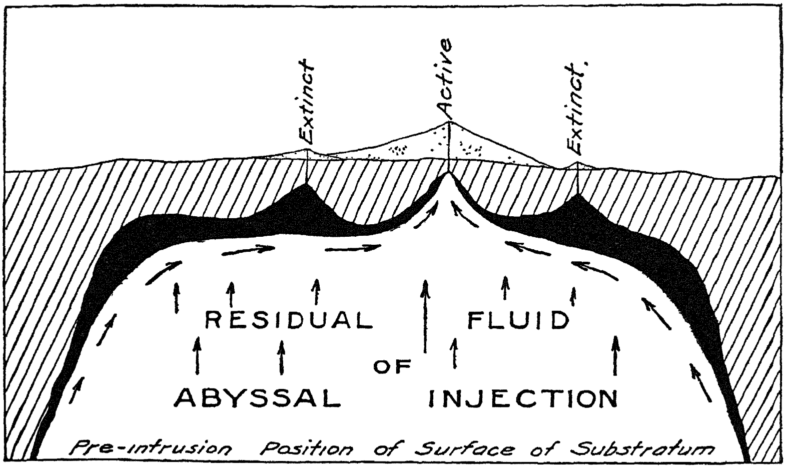

FIG. 126.—Ideal longitudinal section of an abyssal injection, showing the relation of volcanism to the secular rise (*arrows*) of juvenile gas. The middle vent is active because it originates at the highest point (cupola) in the injected body. The other vents are extinct because of this advantage of the middle vent, whereby it robs them of their share of the emanating gas. *Solid black*, the already crystallized material of the injected body; *cross-lined*, country rock. Length of section about 100 kilometers

forming on the surface of the lake, either founder or are dragged down by currents. As they go down, air is carried with them. By "reac-

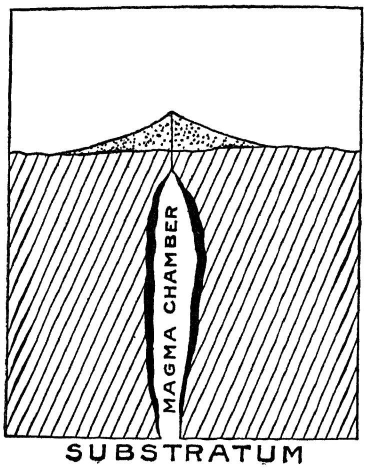

FIG. 127.—Cross section through the middle cone shown in Fig. 126.

tion of lava gases with the air" new heat is generated (Fig. 125). Thus the activity of the volcano is somewhat prolonged.[1]

[1] T. A. Jaggar, Amer. Jour. Science, vol. 44, 1917, p. 165; Weekly Bull. Hawaiian Volcano Observatory, vol. 5, No. 5, 1917, p. 48.

Shepherd finds that the hypothesis is not in accord with the observed ratio of nitrogen to water in the magmatic gas actually analyzed.[1] In any case, this source of the thermal energy to be accounted for can hardly be other than small.

2. A second imaginable source of new energy is the break-up of endothermic compounds that were formed in the basaltic substratum when this earth shell was originated. The idea grew out of a hypothesis of Arrhenius regarding the heat of the sun and remains purely speculative.[2]

3. Less remote from probability is the third hypothesis: that much heat may be produced in the volcanic vent by chemical reactions within its magma when injected into the crust and therefore affected by change of pressure and temperature.[3] In order to illustrate the suggestion, a large number of equations, conceivably corresponding to these shifts of eouilibrium, were entered in the 1911 paper and copied in "Igneous Rocks and Their Origin." It does not seem worth while to repeat their statement here. Figures 126 and 127 will tend to make clear the way in which the gases are concentrated from an abyssal injection. Naturally no attempt is made to delimit the regions where the gases move respectively by pure molecular diffusion and by gravitative transfer in the form of bubbles.

In 1913, Day and Shepherd published the well-known results of their researches at Kilauea.[4] With some emphasis they adopted the third of the foregoing suggestions regarding possible furnace heat at central vents. After proving by chemical analyses the lack of chemical equilibrium among the volcanic gases, and offering specimen equations showing that heat should be given out as the various equilibria shift, they wrote (page 600):

> If the reactions quoted above afford a proper measure of the order of magnitude of the heat quantity thus released within the tube and surface basin of the volcano, we have here happened on an enormous store of volcanic energy which reaches its maximum temperature at the surface itself.

Nine years afterwards, Allen, another member of the staff of the Geophysical Laboratory at Washington, discussed the chemistry of the Kilauea gases and came to a different conclusion:

> On the whole it does not seem probable that very large stores of chemical energy are to be found in the gas reactions of a magma compared with the specific heat of the gas-free lava. It can not be denied, however, that other

[1] E. S. Shepherd, Bull. 61, Nat. Research Council, Washington, 1927, p. 261.
[2] S. Arrhenius, Worlds in the Making, New York, 1908, p. 91.
[3] See R. A. Daly, Proc. Amer. Acad. Arts and Sciences, vol. 47, 1911, p. 47.
[4] A. L. Day and E. S. Shepherd, Bull. Geol. Soc. America, vol. 24, 1913, p. 573.

reactions in the melt, such as the associations of hydrates or reactions between the non-volatile substances, may be of significance.[1]

In 1924, Day reiterated his belief in the considerable efficiency of gas reactions. Still later Shepherd remarked:

> Of the suggested reactions, that between sulfur and carbon dioxide could furnish the most heat, and if the total heat of this reaction could be transported and transformed in this way the reaction could supply the necessary heat for a hundred-meter lake without an incredible rate of gas evolution at the lake surface.[2]

Nevertheless, Shepherd is now of opinion "that such an hypothesis is unnecessary" and prefers to assume, as above noted, that the heat at a crater is supplied chiefly by the continuous flow of magma, upward to the crater and then downward, intrusively, into the surrounding "porous" rocks. It is safe to say that Shepherd has discarded a promising speculation for one most unpromising.

Thus the highest authorities on the Kilauea gases do not agree about the value of exothermic gas reactions for the thermal need of a volcano. They do agree, however, that there is here a true furnace effect. Anything like its accurate measurement is clearly a matter of extreme difficulty. Still more obscure is the quantitative value of exothermic reactions among the non-volatile constituents of lava. But, until future research shall prove the inadequacy of the hypothesis, it seems wise to hold it as part of a working basis for understanding prolonged activity at a central vent.

Gas Fluxing.—Juvenile gas is thought to act in two ways: as a positive heater and as a phase enforcing convection. The effect is to keep fluid the top part of the lava column during the volcano's activity. The conception as a whole may be called the *gas-fluxing hypothesis*. If the crater becomes floored with more viscous lava, the emanating gas issues under higher pressure and may function as a melting blast, making more perfect the analogy with an artificial blowpipe.

Such blowpiping seems to be a natural explanation of the quiet opening of the Kilauea and Mokuaweoweo vents, as well as the many other pit craters of Hawaii, some of which entirely lack pyroclastic or other evidence of explosion (Fig. 76). Von Wolff, in his comprehensive work on volcanism, adopts the gas-fluxing hypothesis as the best available to account for the persistence and intermittency of action at central vents. Washington similarly explains the emplacement and persistence of activity at the vents of Stromboli and Etna. Of

[1] E. T. Allen, Jour. Franklin Inst., vol. 193, 1922, p. 60.

[2] A. L. Day, Jour. Franklin Inst., 1924, sep. p. 24. E. S. Shepherd, Bull. 61, Nat. Research Council, Washington, 1927, p. 262.

course, no volcanologist can doubt Holmes's statement that gas fluxing is not *the* "fundamental" cause of volcanism. It is but one of several fundamental conditions, and the real problem is to evaluate their relative importance.[1] See Plate I.

DORMANCY AND REVIVAL

Continued activity diminishes the rate of supply of the gas producing heat and transferring heat to the critical place, the crater.

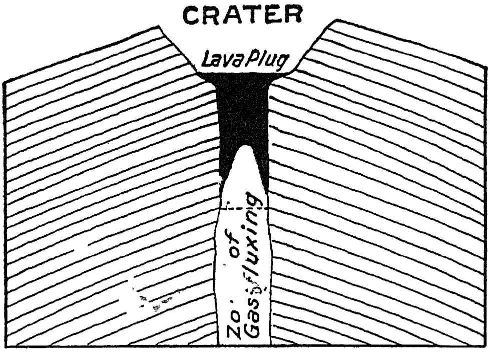

FIG. 128.—Section through upper part of a dormant cone, showing some progress in gas fluxing. The broken line in the middle of the vent indicates the original bottom of the solid plug.

There the lava is gradually chilled, to form a solid plug of some thickness (Fig. 128). The vent may become temporarily so dead that even solfataric action ceases and a forest may flourish within the crater, as has been the case at Vesuvius.

[1] F. von Wolff, Der Vulkanismus, Stuttgart, vol. 1, 1914, pp. 354 *ff*. H. S. Washington, Bull. Geol. Soc. America, vol. 28, 1917, p. 277; Amer. Jour Science, vol. 12, 1926, p. 380. A. Holmes, Geol. Mag., vol. 64, 1927, p. 273.

After the collapse of the floor of Halemaumau in 1924, T. A. Jaggar (Mon. Bull. Hawaiian Volcano Observatory, vol. 13, 1925, pp. 28, 59, 65) found a large "sill" of red-hot rock in the walls of the enlarged crater. Perhaps gas fluxing in place was essential in the generation of this monolithic lens, the lens replacing an approximately equal volume of the old basaltic walls of the crater. This hypothesis would account for an observation described by H. T. Stearns (Water-supply Paper 616, U.S. Geol. Survey, 1930, p. 82): "The stratification of the lava beds seems to pass into the body of the sill and die out, giving the impression that the intrusive body had absorbed large portions of the beds near by."

Was the magma of the intrusive body exposed along the Uwekahuna cliff at Kilauea—and already described by the writer as a laccolith—also generated by the gas fluxing of the associated older lava flows, which were thus locally replaced by a thick monolithic mass imitating an intrusive? In fact, photographs taken since the writer's visit to Kilauea (for example, two published by H. O. Wood, Weekly Bulletin of the Observatory, vol. 4, No. 5, 1916) suggest the possibility that the old flows were in part replaced, rather than displaced, by the material of the "laccolith."

The more or less monolithic plug is comparatively strong; the composite of ash, tuff, and flows at the flanks probably weaker. Nevertheless, activity tends to be concentrated at a single point throughout the growth of a major cone.[1] The beautiful symmetry of a Fujiyama or a Mayon is the result. Probably, therefore, each plug has been weakened along its vertical axis by fluxing heat before explosive removal of the plug closes a dormant period; just as the monolithic crater dome of 1902 at Mont Pelée was largely destroyed and replaced by a similar dome in 1930–1931.[2] The cause of that weakening seems to be fluxing by juvenile gas.

While the plug is intact, the loss of heat is essentially due to conduction and hence extremely slow. Meanwhile the temperature under the cork begins slowly to increase. Hot bubbles of gas continue to rise, feeding the volcanic furnace, and probably heat is transferred upward by leisurely two-phase convection. The accumulated gas may be compressed by crustal movement or by retrograde boiling in depth; if so, heat of compression is added. Gradually the lowest part of the plug becomes remelted, preferably along its vertical axis, where the heat inherited from the last active period is at maximum (Fig. 128).[3] With the consequent weakening of the plug and corresponding increase of gas tension, explosion finally destroys part or all of the plug, and activity at the surface is renewed; dormancy is at an end.

How efficient may be the heating by the compression of gas under the plug is illustrated by certain calculations described in "Igneous Rocks and Their Origin" (page 277).

If the lava column is not kept supported but withdraws for a time from the plug, the compression melting must await sufficient accumulation of gas from beneath or else the return of the liquid because of crustal strain or other reason. The mechanism then works in the way already imagined. Temporary sinking of the liquid would be likely to produce special magmatic stoping, with further danger to the

[1] Naturally the locus of a vent of the central type may be shifted along the course of a master fissure which determined the initial activity. An illustration is figured by A. Rittmann (Zeit. f. Vulkanologie, Erg. Heft 6, 1930, p. 26).

[2] F. A. Perret, verbal communication; also Comptes Rendus, Acad. Sci. Paris, vol. 193, 1931, pp. 1342, 1439.

[3] Concerning the 1905 eruption of Vesuvius, F. A. Perret (Pub. 339, Carnegie Inst. of Washington, 1924, p. 28) wrote: "There can be no doubt that the perforation of the main cone which finally started the great eruption was, in part at least, due to fusion of its walls during this period of superheated conditions in the upper portions of the magma column." Again (p. 77), the still greater activity at the vent in 1906 was facilitated by the fact that "the crateral and sub-crateral lava had re-fused and assimilated all that may have remained of a crater-filling 'plug' or of a 'plastic lining' in the conduit."

integrity of the plug. The surging of the lava column is well illustrated in the history of the Kilauea and Mokuaweoweo vents.

If the volcanic mechanism is nicely balanced, a trifling displacement, like tidal strain, may pull the trigger and renew activity, for which the essential conditions have been long preparing. In general, the change from dormancy to activity does not seem to call for anything so drastic as a strong deformation of the earth's crust.

In conclusion, the gas-fluxing hypothesis appears worthy of a leading place among those that can account for the stubborn persistence in the revival of activity at a Mauna Loa, an Etna, or a Vesuvius. As Perret puts it, the prime cause is probably the gradual development of a "compressed gaseous head" on the lava column.[1]

However, a gaseous head under a plug seems not to be necessary to explain some explosive activity. If the hot plug itself was relatively acid and undercooled (vitreous), its rapid crystallization has been thought to produce, even close to the surface, retrograde boiling and vapor pressure of explosive intensity. In this way Day and Allen account for the 1915 and 1917 eruptions of Lassen Peak. They assume the plug to have been more or less vitreous and undercooled, and therefore capable of dissolving meteoric water, whether this was trapped in buried beds of rock (connate) or due to seepage (vadose). Actual solution of the kind is supposed to have lowered the viscosity of the glass so greatly as to initiate "an avalanche of crystallization" and, at the "second boiling point," vapor pressure high enough to cause the spectacular explosions.[2] Whether diffusion of meteoric water into the vitreous material was fast enough to give the effect described is a question, but the hypothesis of Day and Allen suffices to illustrate some of the many complications of the general problem. Not only juvenile volatiles but also resurgent volatiles, imbibed by the magma under varied conditions, must be considered.

Small Size of Central Vents

The hypothesis accounts for other features of central eruptions. For example, the cross sections of the vents at Kilauea, Hualalai, and

[1] F. A. Perret, Amer. Jour. Science, vol. 36, 1913, p. 605. The plug theory of dormancy seems not incompatible with the conclusion of C. N. Fenner (Jour. Geol., vol. 28, 1920, p. 603) regarding the 1912 eruption of Mount Katmai: that the lava appeared "in the crater and remained comparatively quiet for a certain period before explosive inflation" occurred. No one knows how much free gas escaped before this inflation took place. An essential question is as to how the lava came to "appear in the crater" after a long period of dormancy, when the vent must almost surely have been "corked" by solid rock.

[2] A. L. Day and E. T. Allen, Pub. 360, Carnegie Inst. of Washington, 1925, p. 83.

many other intact craters are all small and of the order expected if the fluidity of each lava column was due to the passage of relatively minute masses of gas. As we have already seen, the succession of Kilauean lava lakes has represented as many *overflows* from one or more narrow, temporary pipes. There as at other centers the visible magma column (Jaggar's "pyro-magma") is greatly flared, and its area gives a highly misleading idea concerning the diameter of the feeding pipe beneath.

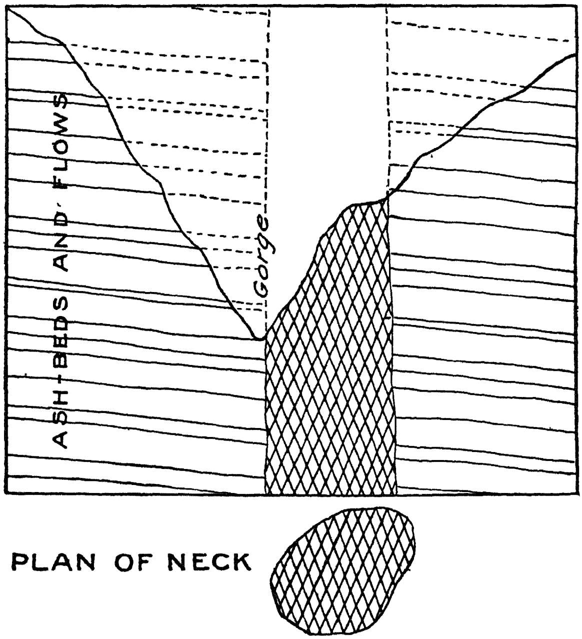

FIG. 129.—Section and plan of a basaltic neck in a lateral gorge of the Iao Valley, West Maui, illustrating the cylindrical form due to gas fluxing. Nearly natural scale; major diameter of the neck about 50 meters. From a field sketch by the author.

Moreover, all the ancient vents exposed as "necks" have small cross sections. The average diameter recorded is well under 300 meters (see Fig. 129 and compare page 150). The pipes of the very largest of the eroded cones are no wider than the pipes of more moderately developed accumulations of lava. There seems to be a *limital size* and that is controlled by the available supply of heat along the axis of the vent. This supply is itself limited largely because it has been brought by emanating gas. In full accord with that conclusion is the typically cylindrical shape of central pipes, a solutional or fluxing form.[1]

[1] A. L. Day (Some Causes of Volcanic Activity, Jour. Franklin Inst., 1924, sep. p. 21) believes that the Kilauea vent consists of "a central collecting tube,

Explosive Types: Magmatic and Phreatic

If no incandescent matter is extruded during an explosion, this is not well classed as strictly magmatic. Following Suess, it may be called *phreatic.* Such an outburst may result from the slow conduction of heat from the conduit of a long dormant cone. Rain water or sea water, connate or temporarily vadose, furnishes the steam pressure if the water had been trapped during the burial of porous flows and pyroclastic beds as the cone grew in size.

Detailed study of the remarkable Rieskessel led Branca (Branco) and Fraas to suggest that the major explosion at that center was

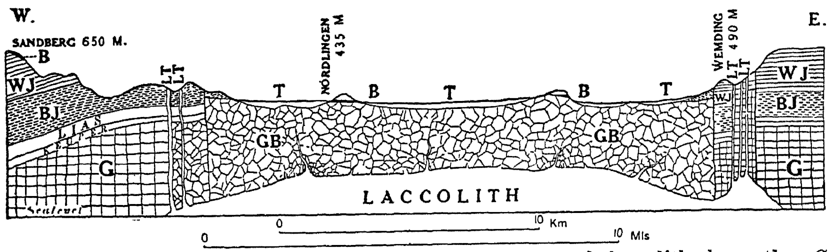

FIG. 130.—Section of the Rieskessel, showing inferred laccolith beneath. *G*, Grundgebirge; *GB*, brecciated granite of the Grundgebirge; *BJ*, Brown Jura; *WJ*, White Jura; *B*, breccia; *T*, Tertiary and Quaternary sediments; *LT*, liparitic tuff (dikes). (*Adapted from W Branco and E. Fraas.*)

phreatic. Geological study had indicated the presence of a large laccolithic mass beneath the Ries depression (Fig. 130). From local disturbances of the magnetic needle in dip and azimuth, Haussmann assumed the foreign mass to be basic (Fig. 131). Its upper surface was calculated to be 2 kilometers below the surface in the Rieskessel itself and about 5 kilometers below the surface outside that depression. The granite and overlying sedimentary veneer were domed during the Mid-Miocene injection of the laccolith. Afterwards the top of the dome was largely destroyed by the explosion, and the catastrophe

with many more or less wide-spreading branches below, leading to local chambers in which crystallization is proceeding under different conditions of temperature and pressure." No good evidence for the truth of this picture is given. The fact that the lava froth issues at different levels in the piles of talus flooring the emptied pit at Kilauea is far from indicating the existence of many feeding channels at depth, below the rubbish of the crater floor. Differential effervescence of the lava and differential fluxing by gases risen through the talus seem competent to account for simultaneous extrusion at the levels observed. T. A. Jaggar (Weekly Bull. Hawaiian Volcano Observatory, vol. 2, No. 27, 1914, p. 107; Bull. Seism. Soc. America, vol. 10, 1920, p. 160) has graphically described basaltic "foam" emanating through cracks 40 to 50 feet above the average level of the Kilauea lake when active in 1914.

was followed by the eruption of a little liparitic tuff at a few points in the new basin. Yet the explosion was occasioned by the tension not of magmatic gas but of connate water in the roof of the laccolith.[1]

Schuster, Löffler, and Bentz have more or less independently concluded that the concentration of gas was due to magmatic "assimilation of the Grundgebirge," so that only a part of the gas was phreatic. Gravity anomalies found by Jung with the torsion balance indicate the existence of a great funnel of explosion centering near the point where

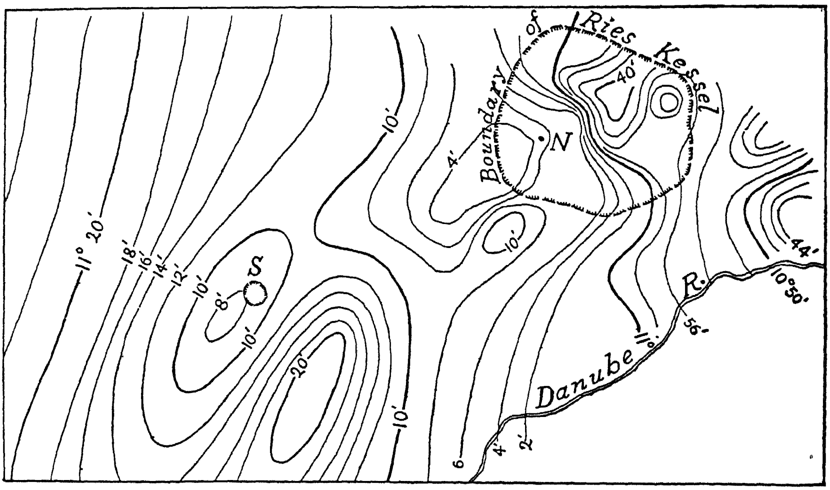

FIG. 131 —Magnetic isogones for 1901, Ries district, Germany. *N*, Nordlingen, *S*, Steinheim basin. The magnetic abnormalities are explained by postulating one or more large basic laccoliths not far from the surface. Scale 1: 880,000. (*After K. Haussmann, Abhand. k. preuss. Akad. Wiss.*, 1904.)

the magnetic anomalies are at maximum and thus tend to confirm the conclusion based on Hausmann's work as to the locus of the activating intrusive body.[2]

According to Bentz, the explosion was violent enough to throw blocks of rock more than 50 kilometers from the edge of the basin (Fig. 132). Nearer the edge the fragments are as large as 70 meters in diameter. Their great size and the centrifugal striation of the underlying bedrock seem to find easiest explanation if we assume that at the time of the explosion the Ries "dome" (Branca and Fraas) or

[1] W. Branco and E. Fraas, Abhand. k. preuss. Akad. Wiss., Berlin, 1901 and 1907. K. Haussmann, *ibid.*, 1904, part 4, 1904, p. 137. According to Sauer, the liparite may represent granite melted by the basic magma.

[2] M. Schuster, Jahresb. u. Mitt. Oberrhein. Geol. Ver., vol. 14, 1925, p. 280. R. Löffler, *ibid.*, p. 26. A. Bentz, Sitzungsber. preuss. Geol. Landesanst., Heft 3, 1928; Zeit. f. Geophysik, vol. 7, Heft 1, p. 1.

Horst (Bentz) was high enough to permit of outwardly directed landslides of the material brecciated by the explosion. However, none of the German authorities postulates so great a height, though Branca and Fraas emphasized the outward thrusts of big slices of rock from the basined area. With them Bentz agrees that there was strong subsidence of the Ries block along ring fractures, after the explosion.[1]

The Steinheim basin of Germany shows similar laccolithic doming, phreatic explosion, and subsidence along peripheral faults, with no eruption of magmatic material.[2]

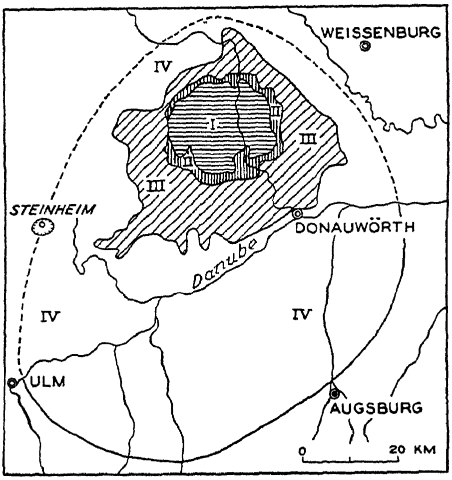

FIG. 132.—Zonal distribution of fractured rock and fragmental material derived from the center of the Ries basin. *I*, sedimented floor of the basin; *II*, belt of blocks and rock slices; *III*, belt of large, rootless blocks, exploded or slid from the basin area; *IV*, belt of isolated projectiles from the basin. (*After A. Bentz, Zeit. f. Geophysik, vol.* 7, 1931, *p.* 3.)

In 1888, a large part of the top of Bandai-San, Japan, was blown off, without extrusion of lava. A priest living on the mountain survived; the exploding vapor was steam and respirable. Destructive as it was, the explosion itself did less damage than the resulting landslide. This seems to be a good example of a phreatic explosion on a volcanic cone (Fig. 133).[3]

[1] A recent boring within the basin shows that the granite is not in place at the high level shown in Fig. 130 (see Bentz, 1928, p. 74). Was the crustal deformation at the Rieskessel genetically somewhat like, though less intense than, that at the "door-knob" dome of Vredefort, South Africa, where "overthrusts" were caused by collapse of the dome?

[2] W. Branco and E. Fraas, Abhand. k. Akad. Wiss., Berlin, 1905, p. 21.

[3] S. Sekiya and J. Kikuchi, Jour. Coll. Sci. Univ. Tokyo, vol. 3, 1889, p. 106.

Lee concluded the Kilburn crater of New Mexico to be of phreatic origin. According to Stearns, the 1924 explosions at Kilauea were of the same character. Fuller explains the Asotin craters of the Snake River region, Idaho, as elongated diatremes that were caused by the

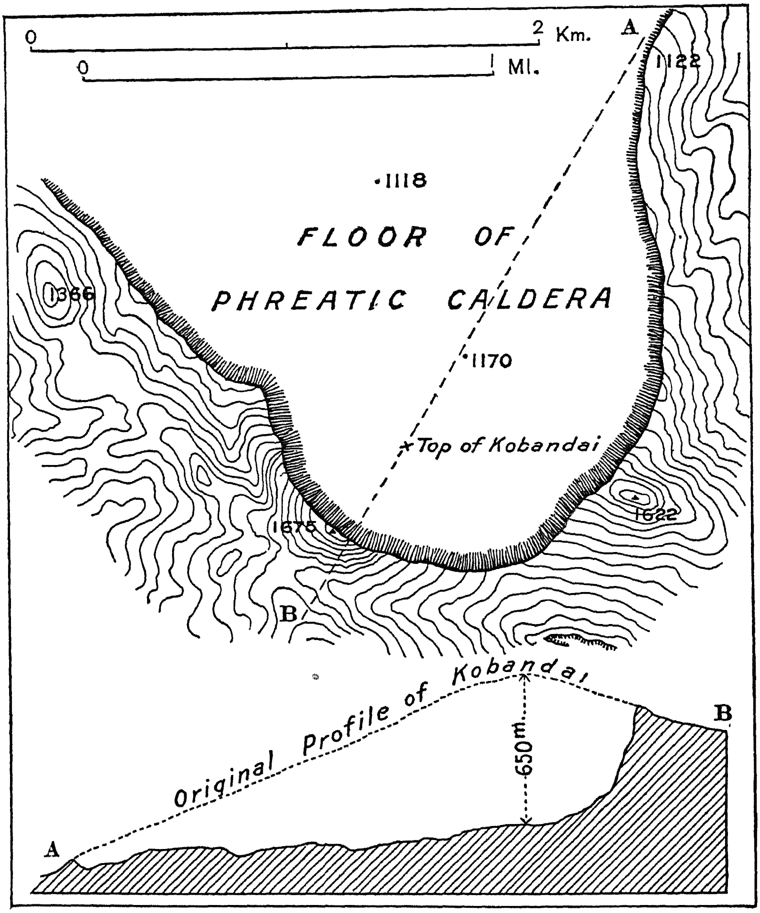

FIG. 133.—Plan and section of the caldera formed phreatically at Bandai-San (Kobandai), Japan, in 1888. Heights in meters. (*After S. Sekiya and Y. Kikuchi, Jour. Coll. Sci. Univ., Tokyo, vol.* 3, 1889, *Plate* 23.)

boiling of water at depth, where eruptive basalt made contact with "water-saturated gravels." Tanakadate states that phreatic explosions at the Japanese volcano Tokati-Dake were followed the next day by "juvenile eruption."[1]

[1] W. T. Lee, Bull. Geol. Soc. America, vol. 18, 1907, p. 218. H. T. Stearns. Bull. volcanologique, Union géodes. et géophys. internat., No. 5, 1925, p. 14, R. E. Fuller, Jour. Geol., vol. 36, 1928, p. 60. H. Tanakadate, Bull. volcanologique, No. 13, 1927, p. 169.

Phreatic eruption means explosion without magmatic extrusion. Kilauea represents magmatic extrusion without important explosion. Between these two types is that to which most active and extinct eruptions are to be referred. However, explosiveness, whether aided by resurgent gas or not, is clearly a subsidiary phenomenon in volcanism. The peaceful Hawaiian vents illustrate the essential problem of central volcanism reduced to its lowest terms. Except abyssal injection, the only indispensable process, according to the author's general theory of the earth, is *quiet exhalation*, from abyssolith or from its satellitic offshoot.

Lava Outflow at Central Vents

Fissure eruptions of basalt have single-flow volumes ranging from 10,000 million to 40,000 million cubic meters (see page 139). In striking contrast are the volumes of the larger recorded flows at volcanic cones, the average being less than 1 per cent of the average for the plateau basalts (Table 43).

Table 43.—Volumes of Flows at Central Vents

Locality of flow	Date	Volume, millions of cubic meters	Authority
Semeroe, Java	1885	300	De Lapparent
Etna	1669	980	Von Waltershausen
Etna	1852	420	Von Waltershausen
Etna	1865	92	Von Waltershausen
Etna	1879	57	Von Waltershausen
Mauna Loa, Hawaii	1852	299	J. D. Dana
Mauna Loa, Hawaii	1855	455	C. H. Hitchcock
Mauna Loa, Hawaii	1880–1881	413	C. H. Hitchcock
Mauna Loa, Hawaii	1907	153	E. D. Baldwin

An explanation of the contrast seems near at hand. The typical plateau basalts are located where the earth's crust was profoundly and widely fractured. Hence, when these vents were opened, the weight of the earth's crust was specially competent to cause extrusion of lava at the surface. In many cases, too, the outlets of the plateau basalts were not so far above sea level as those of the average major cone, a relation still further facilitating the isostatic adjustment between lava column and the earth's crust. Finally, the column of plateau basalt, fresh from the substratum, has, by theory, the higher average temperature and therefore, other things being equal, the lower density and viscosity—conditions favoring voluminous outflow.

Volcanism Originating in Satellitic Injections

Satellitic injections soon lose thermal and hydrostatic connection with their parent abyssoliths. If one of them—laccolith, chonolith, or sheet—has sufficient volume, its thermal energy and gas may suffice to open one or more vents to the earth's surface, according to the methods already described. This kind of volcanism differs, however, in some respects from that due to emanation directly from a wide abyssolith. The more limited size of the feeding chamber means short life and comparatively feeble activity for each vent above the satellitic body. Hence we can understand better the lack of lava flows at many craters, the independent activity of neighboring vents and the chemical dissimilarity of their lavas, the common clustering of many small craters in a region that show no trace, or but few traces, of the alinement of its volcanoes, and the not infrequent evidence of surface deformation in such regions. A hypothesis that does all these things is one of no mean strength.

An analogy may first be cited. The blowholes or driblet cones, so common on deep basaltic flows, are continued in their brief activity by the thermogaseous energy of lava quite removed from the parent vent. The blowholes on the bulges or tumuli of ropy flows in Hawaii or Réunion are particularly instructive, for the tumuli, when just formed, represent minute laccoliths of still-fluid lava, capped by recently frozen lava crust (Fig. 69).

To the weight of analogy is added that of *a priori* reasoning. With few exceptions the published theories of igneous action lead to the expectation that some volcanism originates in magmatic satellites. Many such bodies have been exposed by erosion; it would be a matter of distinct surprise if none ever perforated its roof.

But field observation must make the compelling test. Have we any active example? Can we find evidence where erosion has enabled the study of volcanic anatomy? Each method of testing has its own difficulty. In the first case the satellitic injection is inaccessible and can be located only through inference; in the second case denudation may have destroyed the conduit above and thus some of the required evidence, while gradually exposing the feeding, injected mass. Yet the facts of the field do seem to point to the truth of the principle.

Considering the relations of the Hawaiian vents, it seems justifiable to class Kilauea as the intermittent vent of a liquid, laccolithic, lopolithic, or chonolithic injection, sealed off completely from the Mauna Loa column of magma. Thus we can understand why Kilauean activity has been so much less intense since 1900 than it was during much of the nineteenth century. We have seen (page 191) that the

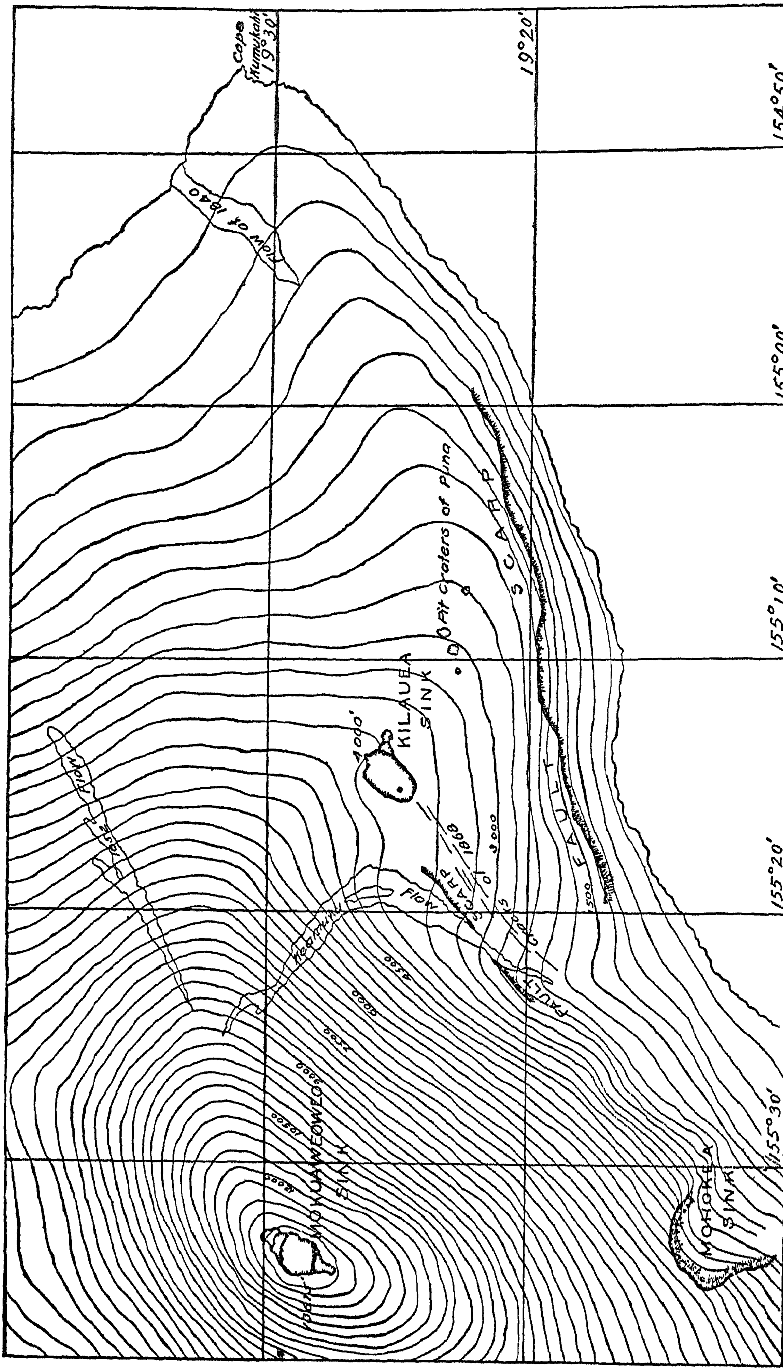

FIG. 134.—Map showing that Kilauea, like the Puna pit craters, is a hole fluxed through a gently sloping plateau, as if the fluxing gas emanated from a floored body injected into the flank of Mauna Loa   Scale 1:530,000; contours in feet.

same hypothesis accounts for the hydrostatic independence of the Kilauea and Mauna Loa vents when simultaneously active (Fig. 134). The double glow registered in one of Jaggar's night photographs eloquently illustrates the case.[1] Naturally in another sense the two vents are not independent; seismic shocks sent out from the Mauna Loa center may change the rate or quality of magmatic activity at Kilauea. Sympathy of that kind does not compel belief in any liquid connection underground. The supposition that the many Puna craters are older vents from the same local chamber that now feeds Kilauea (Halemaumau) can explain their short lives and weak eruptivity. A beautiful map showing the whole group of pits has been published by the United States Geological Survey.[2]

After his visit to Hawaii, Penck adopted the laccolithic hypothesis for Kilauea. Recently Jaggar and Finch have published an important observation bearing on the subject. By actual measurements they showed that the ground around the volcano, for a radial distance of about 30 kilometers, sank after the explosions of 1924, as if the convulsions were associated with volume changes in a more or less circular magmatic chamber some 60 kilometers in diameter. Although other causes for the slight basining are readily conceivable, none seems more worthy of emphasis than that which would identify the postulated "chamber" with the source of Kilauean activity.[3]

Many analogies may be suspected among the lateral craters on the flanks of major cones. Kotô regards the 1914 lateral eruptions of Sakurajima as owing their energy to magmatic bodies that were satellitic with respect to that feeding the main vent of the volcano.[4] The forty-five craterlets ranging along the foot of "New Mountain" at Usu-San, Japan, are other possible examples, developed in recent years. This remarkable deformation of the land surface was clearly due to magmatic injection not far below, and the craterlets seem most

[1] T. A. Jaggar, Amer. Jour. Science, vol. 40, 1915, p. 624.

[2] Water-supply Paper 616, 1930, Pl. I.

[3] W. Penck, Zeit. Gesell. Erdkunde, Berlin, 1912, p. 6 T. A. Jaggar and R. H. Finch, Proc. Third Pan-Pacific Congress, Tokyo, 1926, pp. 679, 686.

F. von Wolff (Der Vulkanismus, Stuttgart, vol. 2, Teil 1, 2te Hälfte, 1929, p. 737) has listed the different explanations of the independence of Kilauea and Mauna Loa. Against the laccolithic hypothesis he urges the supposed breakdown of an argument from analogy, drawn from the intrusion at the Uwekahuna cliff, Kilauea. Of course, that breakdown might have been absolute without essentially affecting the problem. But von Wolff's acceptance of the arguments adduced by Cross, Powers, and Washington in favor of regarding the gabbroid body as the filling of a lava tunnel, rather than as a laccolith, is quite unwarranted. No lava tunnel of the required dimensions has ever been described, and we may well doubt that such an extensive cavity in the rocks of the actual locality was mechanically possible.

[4] B. Kotô, Jour. Coll. Sci., Univ. Tokyo, vol. 38, 1916, p. 144.

easily explicable as openings caused by the independent activity of the injected mass of magma.[1]

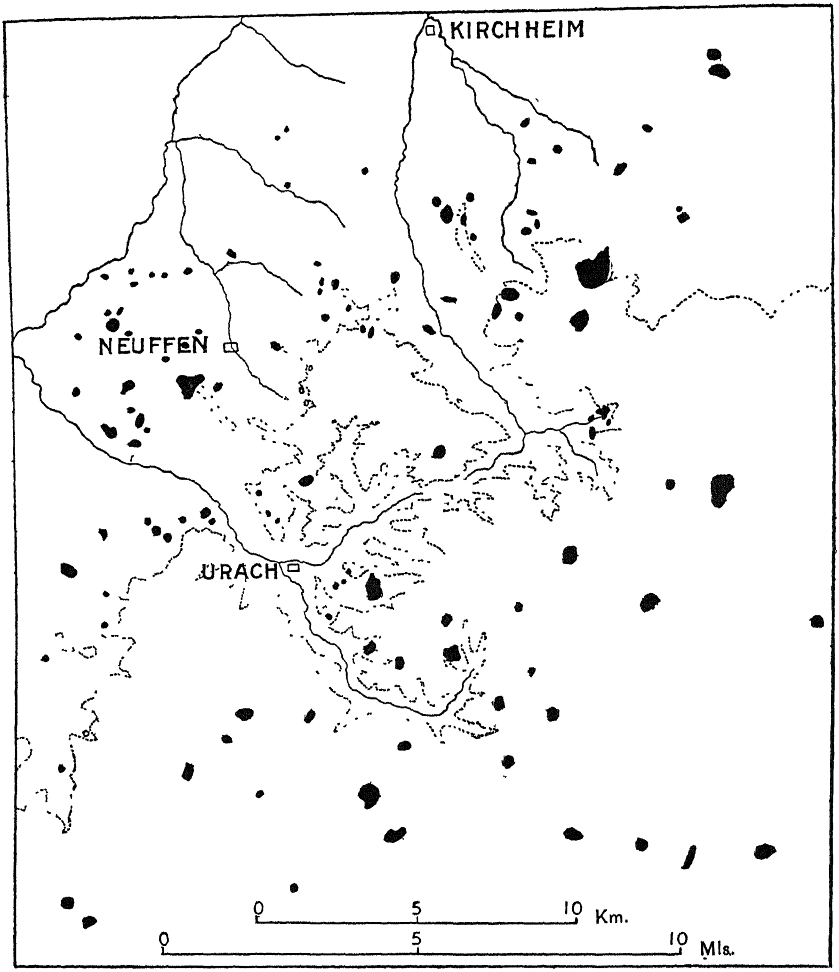

FIG. 135.—Map of part of Swabia showing positions (*black spots*) of "Vulkan-Embryonen." The *dotted line* is the edge of the Swabian Alb escarpment. (*After W. Branco, Schwabens* 125 "*Vulkan-Embryonen,*" 1894.)

Among the prehistoric analogies we note, first, Reck's description of the crater of the Hrossaborg in central Iceland—a diatreme blown through the roof of a laccolith.[2]

[1] According to F. Omori (Bull. Imper. Earthquake Committee, vol. 5, No. 1, p. 1) and Y. Oinouye (Jour. Geol., vol. 25, 1917, p. 287), the "New Mountain" was formed by an intrusion with the shape of a spine, dome, or plug. D. Sato (Bull. Imper. Geol. Survey Japan, vol. 23, No. 1, 1913) believed the intrusion to be of the laccolithic kind.

[2] H. Reck, Monatsber. deut. Geol. Gesell., vol. 62, 1910, p. 316.

After extraordinarily thorough study of the Mid-Miocene eruptions in Swabia, Branco concluded that the Urach region is underlain by a *kuchenförmige Masse*, or laccolith. In ground plan the estimated diameters range between 30 and 45 kilometers. Its position coincides with that of a low, broad doming of the Jurassic strata of the Bavarian Alb. The frontal escarpment of the Alb has been eroded back at least 25 kilometers since the volcanic epoch. On the top of the Alb plateau are 38 tuff vents; the belt occupied by the ragged escarpment has 35 more; and the *Vorland*, or region traversed by the escarpment in its southward retreat, bears 54 tuff vents and 5 basaltic vents (Fig. 135). No lava flows took place on the Alb; the few lava necks became visible because of denudation of the *Vorland*. The largest explosion funnel does not exceed 1 kilometer in diameter. The average diameter of the 132 vents is much smaller. Evidently each of these "volcanic embryos" had a short life. Their brief, almost wholly explosive activities, their distribution in a cluster without reference to master fractures, and the doming of the Jurassic beds, all support Branco's laccolithic hypothesis. He found further corroboration in the specially steep thermal gradient measured at the 340-meter boring of Neuffen—about 10 meters per degree centigrade. Branco explained the abnormal temperature by the residual heat of the laccolith.[1]

Hoel compares seven small vents in Spitzbergen with those of Swabia, and Gevers believes a considerable number of the African Stormberg vents to be openings in the roofs of otherwise sealed, magmatic chambers.[2]

The peculiar abundance of small tuff necks of Permian age in parts of Scotland is subject to a similar tentative explanation. Eighty of them have been counted in a Fifeshire area measuring 18 by 10 kilometers (Fig. 136). Sixty vents of Ayrshire are confined to an area measuring 60 by 30 kilometers, and twenty to an area of only 35 square kilometers. In general, Geikie and his collaborators were unable to find any connection between the necks and lines of dislocation. The Carboniferous strata have suffered sievelike perforation like that of the Jurassic beds in Swabia (Fig. 137). In each of the Scottish districts the lower part of the thick Carboniferous series carries thick sills of dolerite. These are mapped as chiefly of Carboniferous date, but Geikie thought that some of the Fifeshire sills at least are Permian. The steady association of tuff neck and sill does not look quite accidental. Emanations of gas from these intrusives or similar injections cutting pre-Carboniferous formations, together with possible tension

[1] W. Branco, Schwaben's 125 Vulkan-Embryonen, Stuttgart, 1894.

[2] A. Hoel, Skrifter Videns.-sels. Kristiania (Oslo), I Kl., 1914, No. 9, p. 14. T. W. Gevers, Trans. Geol. Soc. South Africa, vol. 31, 1928, p. 61.

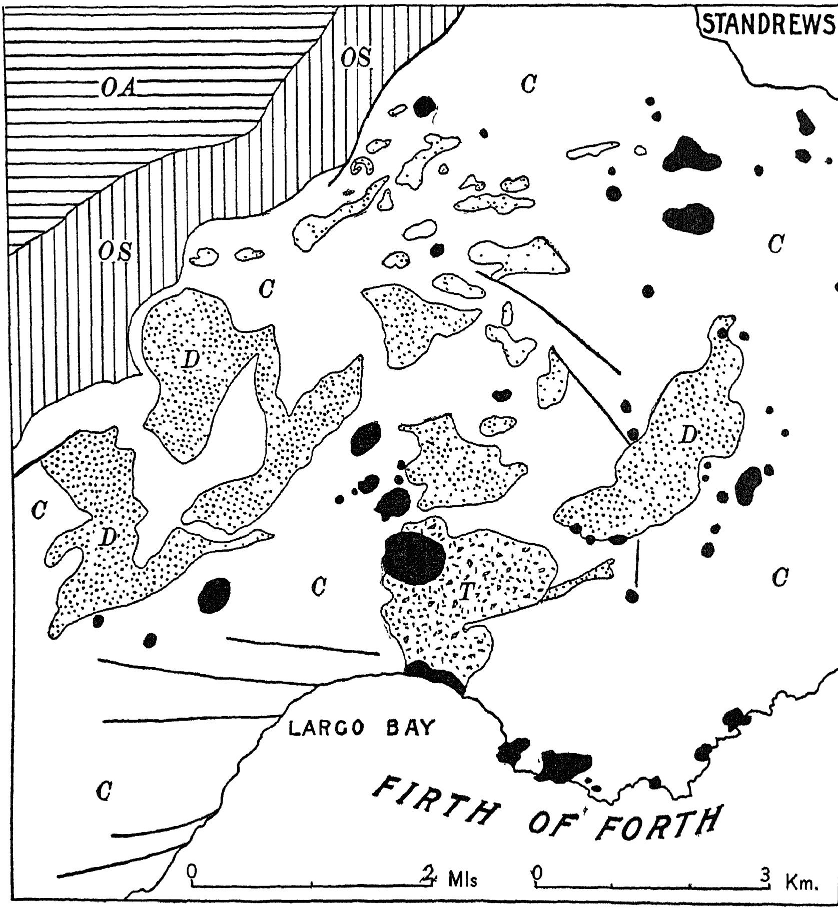

FIG. 136.—Map of part of Fifeshire, Scotland. *OA*, Old Red lavas; *OS*, Old Red sandstone; *C*, Carboniferous; *D*, dolerite sills; *T*, Permian tuffs; *solid black*, Permian necks. The close association of sills and necks suggests the possibility that the latter represent "subordinate" volcanism. (*After A. Geikie, Geology of Eastern Fife, Glasgow,* 1902, *map.*)

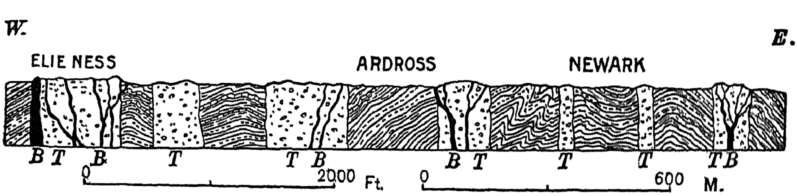

FIG. 137.—Section between St. Monans and Elie, Fifeshire, showing volcanic necks in folded Carboniferous sediments. *T*, agglomerate and tuff; *B*, basalt. Scale approximate. (Same reference as for Fig. 136, page 112.)

of resurgent gas from the heated country rock, seem competent to explain most of the necks. The total activity was limited because each feeding chamber was small.

A similar mechanism, working during the Old Red Sandstone period, may have produced the narrow necks of the Noss Sound region, Shetland, where again thick sills and dikes are exposed. The pipes are filled with agglomerate of sandstone and shale without associated lava.[1]

Rittman has concluded that the phonolites, trachytes, trachybasalts, and other lavas of Ischia were erupted from a laccolithic chamber roofed at about 2 kilometers below the surface of the island.[2]

A Necessary Division of Central Vents

Our general theory demands the recognition of the two kinds of central eruptions. Long and strong activity, large outflow of lava, and alinement in chains will usually characterize the vents originating directly in abyssoliths: what may be called "principal" volcanoes. Brief activity, small output of lava, cluster grouping, and perhaps also some deformation of the surface are expected features of vents originating in satellitic injections: "subordinate" volcanoes. As one or more of these criteria fail, the classification is hard to apply. Nevertheless, the underlying idea has value. We have seen how it bears on the statement that there can be no vitreous substratum beneath a region bearing two simultaneously active craters of differing heights (page 191). It promises to help our understanding of the chemical variety among the lavas of neighboring cones. The magmatic histories of abyssolith and satellitic injection, like those of two satellitic injections of contrasted volumes, are likely to be different. Accordingly, the emanating lavas would vary in character, whether differentiates of pure primary magma or derived from syntectics.

General Summary

In review, central eruptions are seen to be of two kinds. The *principal* class represents emanations directly from abyssoliths. The *subordinate* class originates in magmatic bodies (laccoliths, chonoliths, etc.) that are satellitic with respect to abyssoliths. The localization and common alinement of major vents are explained by the principle of abyssal fissuring and injection. Because of the large size of the corresponding abyssoliths, principal volcanoes show intense activity,

[1] A. Geikie, Quart. Jour. Geol. Soc. London, vol. 48, Pres. Address, 1892, p. 95. B. N. Peach and J. Horne, Trans. Roy. Soc. Edinburgh, vol. 32, 1884, p. 359, and vol. 28, 1878, p. 418.

[2] A. Rittman, Zeit. f. Vulkanologie, Erg. Heft 6, 1930, p. 154 and Fig. 40.

have long lives, and deliver much lava to the earth's surface. Subordinate volcanoes, fed by smaller bodies of magma, are not so characteristically grouped in lines, are less energetic, have shorter lives, and are less capable of extruding lava. In their activities they are largely independent of one another and still more independent of any neighboring principal vents, one result being to add to the petrographic diversity of extrusive rocks.

Continued eruption at a central vent is a heat problem. Primary heat is probably supplemented by the heat of chemical reactions among the constituents, especially the gases, of the volcanic magma. A working philosophy of volcanism should give due regard to the hypothesis that a central vent is a *true furnace.*

The rate of loss of heat at an active crater, chiefly by radiation to the sky, has been roughly calculated; the rate is impressive. Among the methods of transferring heat from the depths, *two-phase convection* is emphasized. It is thought to account largely for the maintenance of prolonged activity, though the melting and blasting effects of gas, rising as a separate phase, are also important. Dormancy and the related periodicity of action are likewise explicable by what, in general, is called the *gas-fluxing hypothesis.*

Progress of crystallization and magmatic differentiation in depth, and the entry of resurgent, tensioned gas into the primary magma all tend to increase the explosiveness of a volcano. Magmatic and phreatic explosions should be distinguished if the tangle of volcanological facts is to be unraveled. Although magmatic heating of rocks charged with connate or other trapped water causes explosion, this pressure of steam is manifestly not the fundamental cause of volcanism. The origin and emplacement of the magma itself are fundamental. It is merely a matter of detail whether or not the upper end of the magmatic column encounters wet rocks, with consequent explosion.

The facts of volcanic geology seem, thus, to cooperate with the facts of plutonic geology in showing that igneous action depends essentially on abyssolithic injection. The magma so thrust into the earth's crust may be either the primary material of the Simatic substratum or secondary liquid, generated by pure melting or by assimilation in the material of the substratum.

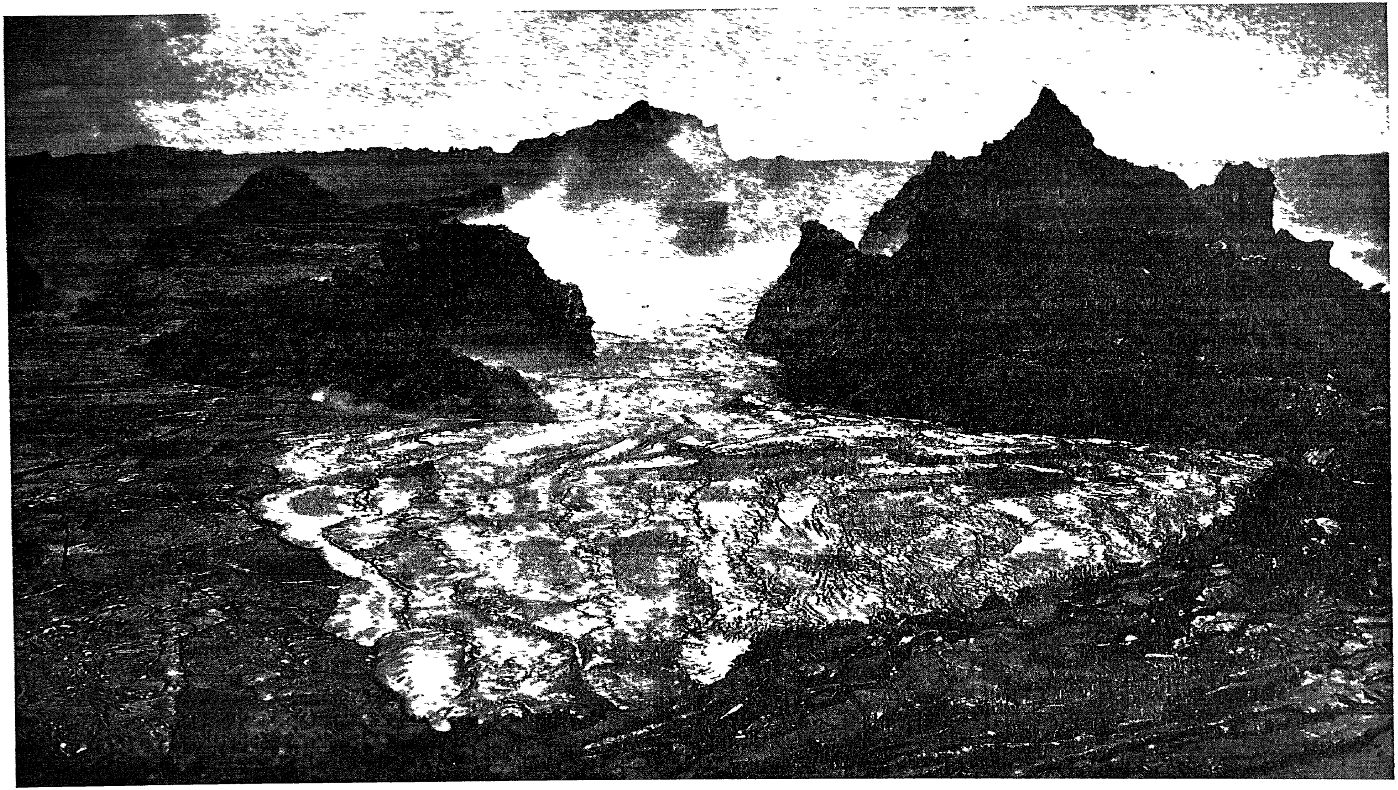

PLATE III.—Lava lake of Halemaumau seen from the north, Sept. 20, 1921. (*Photograph by T A Jaggar, Bull Hawaiian Volcano Observatory, vol.* 9, 1921, *pp.* 140, 146)

(*Facing p* 394.)

PART III: APPLICATION OF THE GENERAL THEORY

A general theory of igneous activity and its results have been outlined in Part II. There and in Part I are references to facts representing as many tests of the theory, which, if sound, should hold its own after specific study of individual rock clans. At present this further testing cannot even approach completeness. Among the reasons is our ignorance of many physicochemical conditions. Fundamental principles have been brilliantly established by the physical chemists, but exact application to most petrogenetic questions remains a task for the future. Meanwhile the petrologist can be guided to some extent by the results of analytical chemistry, combined with the facts of the field. Accordingly, the survey of the clans in Part III will involve comparisons among analyses of single rocks and among average analyses of rock species. The treatment is fragmentary and does not pretend to cover all the scattered data of the contemporary science. Almost throughout the long list of types differing chemically from the primary basalt, the genetic mechanism is thought to be more or less complex. In varying proportion it includes crystal fractionation, pure melting, selective fusion or crystal fractionation in reverse, assimilation, and resurgency of the secondary fluids. The importance of resurgent, as well as juvenile, volatiles in the development of the syenitic and feldspathoidal clans is once more indicated.

To save space, the list of species constituting each clan will here be omitted or else greatly abridged.

CHAPTER XVI

GABBRO CLAN

Included Species

In the gabbro, gabbro porphyrite, and basalt families Rosenbusch (1908) placed more than fifty species. He believed that the essexite and trachydolerite families belong to a quite different line of descent. However, close field and chemical association warrants the inclusion of these two families also in the major group here called the gabbro clan. On the same grounds, orthoclase basalt, mugearite, picrite-basalt, and ankaramite are included, while leucite basalt and crinanite, though by definition belonging to the feldspathoidal clans, will be discussed in the present chapter.

Mere differences of geological age or minor differences of texture, degree of crystallinity, or degree of alteration have prompted the invention of a number of the varietal names. The more significant problems of origin arise in connection with the greater chemical contrasts and the resulting mineralogical peculiarities.

Some members of the clan appear to be direct differentiates of plateau basalt, the primary magma held to be responsible for post-Archean igneous action, and itself of somewhat variable composition (see page 200). Other species are not obviously in such a simple filial relation. These seem best explained as products of interaction between the vitreous substratum or liquid plateau basalt, on the one hand, with both acid and basic rocks of the crust, on the other. Examples of the nearly or quite pure differentiation will first be considered, and then some species of the more complex origin.

Oceanite (Picrite-basalt), Olivine-rich Diabase, and Ankaramite

That the strongly mafic oceanites and certain other olivine-rich types are due to the concentration of olivine in basaltic liquid seems fairly clear. One objection to the idea that the early-formed crystals of this kind were sunk by simple gravity is the comparatively uniform distribution of the olivines actually observed in the oceanites. If we assume the sunken crystals to have been dissolved by, and later recrystallized in, somewhat superheated basalt at depth, this theoretical trouble would disappear. Whatever may be the mechanism, it is worth while to glance at the result of gravitative segregation of

the olivine substance in a deep layer of normal basalt. Three examples will be cited, represented by the picrite-basalt of Hawaii, the olivine diabase layer of the Palisades sheet in New Jersey, and a sill of the Shiant Isles.

The average of ten good analyses of the most abundant Hawaiian basalts, which are remarkably alike, is given in column 1 of Table 44. Column 2 gives the average analysis of three phenocrystic olivines from the picrite-basalt at different Hawaiian localities; these mineral analyses also show only minor differences.

TABLE 44.—AVERAGE ANALYSES OF BASALT AND PICRITE-BASALT (OCEANITE)
(All reduced to totals of 100)

	1	2	3	4	5
Number of analyses averaged	10	3	.....	3	10
SiO_2	50.29	39.97	46.86	46 62	45 6
TiO_2	3.03	.08	2.05	1.71	1 7
Al_2O_3	12 92	46	8.77	8.68	8 3
Fe_2O_3	1 48	1 14	1.37	2.04	2.3
FeO	9.77	10.31	9.96	10 52	10 2
MnO	.14	.11	.13	.14	.1
MgO	8.07	46.84	21.00	20 86	21.7
CaO	10.84	.13	7.25	7.15	7.5
Na_2O	2 26	.29	1.60	1 41	1.3
K_2O	.46	.10	.34	.28	.4
H_2O	.38	.20	.32	.23	.6
P_2O_5	.36	.....	.23	.14	.3
Cr_2O_3	.....	.13	.04	.12	
(NiOCo)O	. . .	24	08	10	

1. Average dominant basalt of Hawaii.
2. Average early-formed olivine in 1.
3 Composition of mixture of 1 with 50 per cent of 2 by weight.
4. Average picrite-basalt of Hawaii.
5. Average oceanite of the world, according to G. W. Tyrrell (The Principles of Petrology, London, 1926, p. 131).

Column 3 states the result of adding 50 per cent of the olivine to the basaltic liquid and reducing to a total of 100 per cent. Column 4 gives the average of three analyses of the picrite-basalt.[1] The similarity of columns 3 and 4 is close, and, if we make the unproved assumption that the olivines of the basaltic and picritic types are chemically identical, we see how this might be a simple case of crystal fractionation under gravity. Of interest is Tyrrell's "average oceanite" (column 5).

[1] The original data are taken from papers by H. S. Washington (Amer. Jour. Science., vol. 6, 1923, p. 338) and M: Aurousseau and H. E. Merwin (Amer. Mineralogist, vol. 13, 1928, p. 559).

In a similar way the olivine diabase layer of the Palisades sheet will be later compared with the chilled contact phase of the sheet, a phase that closely represents the original liquid.

A point of detail may be noted. The iron oxides, totalized as FeO, are slightly higher in the picrite-basalt of Hawaii than in the dominant basalt of the island; has some oxide of iron accompanied the olivine in its concentration?

The ankaramites appear to be analogous mixtures of approximately basaltic liquid with concentrated crystals of pyroxene, derived from the same original (basaltic) magma (see column 73, Table 1).

Walker describes an analogy, found in the main western sill of the Shiant Isles, off the Scottish mainland.[1] Its floor is exposed, but the roof has been eroded away. The residual thickness is at least 500 feet or 150 meters. The uppermost phase, somewhat more than 120 meters thick, is a crinanite or olivine dolerite with accessory analcite. This is underlain in succession by a more basic olivine dolerite, about 25 meters thick, and, at the floor by 3 meters of picrite. Walker gives the mineralogical compositions in percentages:

Phase	Height above floor, feet	Specific gravity	Olivine	Augite	Plagioclase	Iron ores	Zeolites
A	400	2 94	8	24	61	4 5	2 5
B	250	2 95	11	29	54	4	2
C	125	2 97	12	24	60	3	1
D	70	3 00	20	21	54	3	2
E	45	3.02					
F	30	3 03	31	17	50	2	
G	15	3 09					
H	0	3.11	59	10	26	2	3
X (olivine-basalt sheet, eastern Shiant Isles)	...	2 81	13	15	61	6	5 (zeolites or glass)

Walker assumes the magma before differentiation to have had a composition close to that of a dolerite in Skye (column Y, Table 45), itself much resembling the rock of an undifferentiated olivine-basalt sheet, injected into the differentiated rocks of the Shiant Isles (column X). He accounts for the picritic phase by sinking of early-formed olivines in the main sill. That this was not the sole cause of the differentiation seems clear when one notes the increase of lime in the crinanite (column C) over that in more normal dolerite (column X), without a corresponding increase of the alkalies. This fact suggests

[1] F. Walker, Quart. Jour. Geol. Soc. London, vol. 86, 1930, p. 361.

TABLE 45.—ANALYSES, SILL OF THE SHIANT ISLES

	C	F	H	X	Y
	Crinanite	Olivine dolerite	Picrite	Olivine basalt	Dolerite of Skye
SiO_2	47 83	45 07	40.62	46.48	47.64
TiO_2	2 86	.83	.82	2.00	1.27
Al_2O_3	15.31	14.43	8.93	15.59	14.15
Fe_2O_3	1.15	.80	.57	4.54	5.18
FeO	9 22	10.69	12.61	8 62	7.96
MnO	.36	.33	.39	.28	.33
MgO	6 60	14.61	26.31	9.19	7.38
CaO	12.38	9.74	5.64	8.98	11.71
Na_2O	2.53	1.75	1.32	2.79	2.38
K_2O	40	.34	.13	.71	.71
H_2O+	1.28	1.05	2.19	.85	1.44
H_2O-	.28	.35	.61	.81	.19
P_2O_5	.16	.10	.15	.11	.09
Rest	.08	.05	.07	.14	.10
Total	100 44	100.14	100 36	101 09	100.53

the independent extraction of volatile or mobile solutions of (preferably hydrous) aluminosilicates of the alkalies, and their rise into the roof from the horizon of the column C rock.

FELDSPAR-RICH BASALTS

According to Bowen, the "porphyritic central magma-type" of Mull represents a concentration of early-formed crystals of labradorite-bytownite in basaltic magma. The best estimate of the Mull (Thulean) plateau basalt is probably that made by Washington (column 1, Table 46).[1]

[1] H. S. Washington, Bull. Geol. Soc. America, vol. 33, 1922, p. 797.

It is not easy to see why the authors of the Mull memoir believe the plateau basalt of their region to have had the composition shown on p. 14 of the memoir. Analcitic rocks are included in their average—also intrusive rocks whose chemical identity with plateau basalt is not assured. Moreover, most of the rocks analyzed and averaged were more or less weathered, as shown by the high content of water and by the microscopic petrography. For all three reasons the oxide proportions in the published average doubtless differ from those in the original magma. Small as the differences may be, they affect results considerably when the addition-subtraction method of discerning the process of differentiation is used. The actual oxide proportions given in the memoir average for the plateau basalt really seem to indicate some concentration of mafic constituents beyond that normal to plateau basalt in general or that found for Thulean plateau basalt by Washington; other differences are also apparent. W. Q. Kennedy (Summ. Prog. Geol. Survey Great Britain, 1930, part 2, p. 61) too has questioned the decision of the authors of the Mull memoir as to the chemical nature of the parent plateau basalt in the region.

Column 2 of the table gives the average composition of the porphyritic central magma type. Its high lime and alumina are accounted for, if about 40 per cent of basic plagioclase had been added to the plateau basalt, though the titania comes out too high and the magnesia too low. These discrepancies would be lessened if a little titaniferous magnetite and magnesia-rich olivine settled out while the feldspar was being concentrated, or just after that event.

TABLE 46.—BASALTIC MAGMA TYPES IN THE ISLAND OF MULL
(Calculated as water free and to totals of 100)

	1	2	3
Number of analyses averaged	33	7	10
SiO_2	48.33	47 78	51 94
TiO_2	2 76	.93	2 01
Al_2O_3	14 14	21.70	13.55
Fe_2O_3	3.65	3.30	4.05
FeO	9 55	4 85	9 16
MnO	22	.22	.31
MgO	6 94	5.48	5.12
CaO	10.00	13.10	9.52
Na_2O	2 94	2.09	2.76
K_2O	1 03	.40	1 28
P_2O_5	.44	.15	30
Specific gravity	. .	2 875	2 86

1 Average Thulean plateau basalt (Washington)
2 Average porphyritic central magma type, Mull.
3 Average non-porphyritic central magma type, Mull.

The comparatively even distribution of the feldspar phenocrysts, instead of their notable clumping-together, is a problem like that relating to the olivines in the oceanites, and again one must ask if resorption of the crystals did not, here also, take place. If it did, some superheat would be required in the dissolving magma, but the degree of the superheat need not be regarded as extremely high. In Chapter XIII we saw some reason to assume at least 150° of superheat as possible in plateau basalt.

Bowen rejects the re-solution hypothesis on the ground that

> . . . there would be available somewhere a rapidly cooled mass having the total composition of the Porphyritic magma-type and containing all of its plagioclase as a constituent of the aphanitic ground. There are no such rocks in the region, at least, none have been found.[1]

Such negative evidence is not likely to be final for those who prefer to avoid other troubles by postulating re-solution of the "excess" feldspars. Moreover, one may ask whether the persistence of the

[1] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 136.

porphyritic character, even in contact phases, is connected with the high velocity of crystallization of the more basic plagioclases?[1]

NON-PORPHYRITIC CENTRAL (THOLEIITE) MAGMA TYPE OF MULL

Bowen, like the authors of the Mull memoir, regards this magma (column 3, Table 46) as residual after the subtraction of certain compounds from the plateau magma. The compounds were listed as follows:

	Percentage
Plagioclase ($Ab_{37}An_{63}$)	53
Olivine:	
Forsterite	16
Fayalite	11
Diopside	7.5
Magnetite	4.5

The result is subject to some doubt because of the high ratio of FeO to MgO in the olivine, namely, 77:91. This is much higher than the ratio expected at the stage of crystallization assumed.[2] The material to be subtracted differs considerably if the better, Washington average for the parent magma be taken, and calculation shows that mere subtraction of any assemblage of crystals likely to form in the plateau basalt does not give the non-porphyritic central type of liquid. Hence, while crystal fractionation may have dominated, other processes seem also to have been at work.

In fact, the authors of the Mull memoir are not content with explanation by the one mechanism but have considered the possibility of a small amount of assimilation of the more siliceous country rock by the plateau basalt magma. Slight external influences of the kind would have manifest importance in the problem.

Incidentally we note once more a major difficulty for the hypothesis that practically all igneous rocks, including those of post-Archean dates of eruption, have been directly derived from basaltic liquid by crystal fractionation. According to Bowen's calculation, at least half of the original liquid must have crystallized and separated in order to give the non-porphyritic central type of magma by this method, and yet the residual liquid is still fairly described as a basalt. This affords a lively idea of the stupendous quantity of basalt that would

[1] See A. L. Day and E. T. Allen, Pub. 31, Carnegie Inst. of Washington, 1905, pp. 36–39. H. H. Thomas (The Geology of Ardnamurchan, etc., Memoir Geol. Survey Scotland, 1930, p. 98) is inclined to favor the view that much of the basic plagioclase of the porphyritic central rocks had been accumulated by gravity, then resorbed by the receiving liquid, and finally recrystallized with practically the original composition of those feldspars.

[2] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 77.

have to crystallize in order to make a batholith of granite by the same process. Is such volume credible in the case of any post-Archean batholith?[1]

"Alkaline" Basalts and Intrusive Equivalents

The close association of the "alkaline" and "subalkaline" rocks in the field is well illustrated by types that are clearly of basaltic habit. Table 47 gives a list of examples. According to the general theory, the alkaline basalts are essentially derivatives of plateau-basalt magma. The mechanism involved is a question. Its brief discussion will center around the examples designated by the average analyses of the table.

The relations of the alkalies, lime, magnesia, and iron oxides seem to forbid our assuming the species here considered to have originated through the mere single-course fractionation of saturated plateau basalt but suggest actual addition of alkalies to this magma or to its residual liquids. Several conditions for the importation may be conceived: (1) by gaseous transfer of feldspathic molecules or of aluminates of the alkalies, (2) by concentration and solution of crystals of the alkaline feldspars, (3) by addition of siliceous-alkaline liquid. While the first process is to be suspected in the cases represented by crinanite and analcite basalt, the third hypothesis is probably the most promising for the other types.[2]

A source for the imported alkaline material is not far to seek, if for any reason selective fusion of holocrystalline gabbro, diabase, or basalt takes place within (xenoliths) or alongside of (walls) the column of liquid which is to be changed by the importation. The crystalliza-

[1] T. Krokström (Bull. Geol. Inst. Univ. Upsala, vol. 24, 1932, p. 211), like Fenner and others, feels the same difficulty. Did the Thulean plateau lavas emanate from different levels in the substratum, so that the non-porphyritic central type of basalt and the true olivine basalt were both primary, undifferentiated magmas? See p. 200; also W. Q. Kennedy, Amer. Jour. Science, vol. 25, 1933, p. 239.

[2] E. Lehmann (Chemie der Erde, vol. 5, 1930, p. 319; Min. u. Petr. Mitt., vol. 41, 1931, p. 8) regards German and Nyassaland basalts with 43.5 to 45.7 per cent silica, 8.2 to 12.1 per cent magnesia, and 1.5 to 1.9 per cent potash as parental basalt. These proportions differ from those found for average plateau basalt. It seems reasonable to suspect that Lehmann's essexite-basalt and "atlantite" both represent plateau basalt modified, particularly by the addition of potash. It may be a relevant fact that the Stöffel basalt of Germany, taken as a parental liquid and "bearing in every respect the characteristic features of plateau basalt" (1931, p. 14) was extremely (*überaus*) rich in volatiles (1930, p. 324). Like the Mull memoir and some other recent discussions, these detailed papers by Lehmann show the importance of being sure of the chemical nature of the parental magma, if it is to be argued that crystal fractionation without addition is the sole method followed by Nature when developing the alkaline suite.

TABLE 47.—BASALTIC MAGMAS RELATIVELY RICH IN ALKALIES
(Analyses reduced to water free and to totals of 100)

	A	B	1	2	3	4	5	6	7	8
Number of analyses in average.....	43	33	6	15	3	4	6	20	34	12
SiO_2	49 70	48.33	45 98	46.44	47 28	51.45	47.42	49.31	49 85	47 41
TiO_2	2.23	2.76	2 06	2.65	2.65	2.19	2.97	1.88	1 70	2 19
Al_2O_3	14 24	14.14	16 02	14 54	16 05	14.88	17.00	18 20	16 88	13 09
Fe_2O_3............	3.66	3.65	3.39	4 09	4 10	5.82	3.25	4.37	4 82	5 41
FeO..............	9.96	9 55	10.53	6.93	8.52	7.73	7.34	5.66	5.43	5.20
MnO	.17	22	.26	16	.09	.40	.....	19	.56	.19
MgO	6 82	6 94	7 54	9 28	5.80	3 56	5.91	4.05	4 48	8 58
CaO	9.55	10 00	9.57	9 51	7.91	7 02	10.31	9.01	7 84	8 38
Na_2O	2.64	2 94	3 43	3 86	4.33	4.34	3.57	4 36	4 60	2 42
K_2O	.70	1.03	.93	1.82	1.49	1.72	1.91	2.31	3.23	6 34
P_2O_5	.33	44	.29	.72	1.78	.89	32	.66	.61	79

A. Average plateau basalt (world)
B. Average Thulean plateau basalt (Washington).
1 Average crinanite.
2. Average analcite basalt.
3. Average "olivine-oligoclase andesite" of Hawaii (Washington).
4. Average mugearite.
5. Average essexite-gabbro.
6. Average essexite.
7 Average trachydolerite.
8 Average leucite basalt.

tion of any of these rocks is fractional, and their residual liquids are more alkaline and of lower temperatures of melting than the corresponding rocks or plateau basalt itself. Fluxing of the holocrystalline rocks begins with the generation of the more alkaline liquid. Formed in depth, this liquid of relatively low density should rise through a column of liquid plateau basalt and increase the alkalinity of the upper part of the column (illustrating a kind of hybridism).

The selective fusion is accomplished in different ways. If plateau basalt, injected into or through a thick mass of solid basaltic rocks, is somewhat superheated and kept stirred, differential melting of these takes place. Similar fluxing is expected if resurgent gas is concentrated in sufficient mass. Moreover, the possibility of selective fusion is directly inferable from the intermittent character of volcanic activity. Lava that was crystallized during the dormant stage of a basaltic volcano is partially melted or gas-fluxed during the succeeding active stage. The new liquid, comparatively rich in alkalies, tends to be gravitatively concentrated in the throat of the volcano at high levels.

Most clearly supported by field observation is the hypothesis last mentioned. It is appropriate in the case of such rocks as the "olivine-oligoclase andesite" of Hawaii and the mugearite of the British region

of dominant Tertiary basalts. Later we shall see that the same theoretical condition may underlie the formation of trachyandesites, trachytes, and allied rocks, so common as small parts of otherwise basaltic cones and exogenous domes.

Basaltic Rocks Poor in Alkalies

Some basalts and dolerites (diabases) carry less soda and potash than plateau basalt and yet otherwise closely agree with it in composition. Illustrative analyses are given in Table 48. Others appear among the analyses of the Mauna Loa and Kilauea lavas of Hawaii.[1] The low content of alkalies cannot be explained by the leaching action of the weather, for the specimens analyzed were notably fresh. Nor does any direct additive process of fractional crystallization serve. Partial removal of the alkalies by resurgent volatiles is conceivable but would be difficult to prove. The problem remains open.

Table 48.—Basaltic Rocks Poor in Alkalies
(Analyses reduced to water free and to totals of 100)

	A	1	2	3
SiO_2	49.70	52 51	50.18	52.25
TiO_2	2.23	1.07	2.20	1.30
Al_2O_3	14 24	15.38	13.70	14.92
Fe_2O_3	3.66	1 00	3.72	1 13
FeO	9.96	9 17	9.08	9.21
MnO	.17	.53	.21	.27
MgO	6.82	7.08	6.58	7 72
CaO	9 55	10 60	11.44	10.78
Na_2O	2.64	1 52	1.70	1.86
K_2O	.70	.87	.73	.43
P_2O_5	.33	.27	.46	.13

A. Average plateau basalt (forty-three analyses).
1. A Karroo dolerite (R. A. Daly and Tom F. W. Barth, Geol. Mag., vol. 67, 1930, p. 101).
2. A Deccan basalt, Padmi, India (H. S. Washington, Bull. Geol. Soc. America, vol. 33, 1922, p. 774)
3. Diabase, Weehawken, New Jersey (analysis VI in J. V. Lewis, Ann. Rep. State Geologist of New Jersey, 1907, p. 121)

Quartz Diabase and Allies

Many rock bodies are chemically and mineralogically near the hypabyssal or plutonic equivalents of basalt and yet contain quartz, free or in micrographic intergrowth with feldspar. These types include quartz diabases, quartz dolerites, quartz gabbros, some quartz-bearing porphyrites, and quartz basalts. Of much the same chemical composition are quartz norite, some orthoclase gabbros, and some mica gabbros. Different ideas of origin have been entertained.

[1] H. S. Washington, Amer. Jour. Science, vol. 6, 1923, pp. 122, 342.

I. Wahl and also Thomson attribute quartz diabase to the direct crystallization of a primary magma, essentially unchanged either by contamination or by any form of differentiation.[1] As noted on page 436, it is conceivable that the abundant quartz diabase of the late Pre-Cambrian was derived from an eruptible earth shell that represented the transition from the primitive Sial to the still deeper olivine basalt. However, there are objections to assuming a wholly primary origin for all quartz diabases of much later dates of eruption.

Neither the quartz diabases nor their close allies bearing free silica are recorded from the islands of the central Pacific, and in general they are exceedingly rare among the many volcanic piles built upon the floor of the open ocean, while they are found on all the continents. This distribution is not readily explicable if all quartz-diabase magma is an independent, primitive, unmodified constituent of the earth.

Further, the quartz-bearing rocks considered are commonly in intimate field association with normal basaltic, diabasic, or gabbroid rocks. The relation may be one of gradual transition, or otherwise such as to render the independence of origin highly improbable—a mechanism by which the two primitive liquids could have been kept separate and yet simultaneously eruptible is hard to imagine. The gradual nature of the transitions is illustrated among the many sills and laccoliths listed in Table 40. Close association of quartz-free and quartz-bearing members of the clan in bodies separate both in space and in times of eruption is likewise evident. A well-studied example is furnished by the group of Carboniferous olivine dolerite and quartz dolerite sheets of Fifeshire, Scotland.[2]

II. Bowen regards the quartz-bearing members of the gabbro clan as pure differentiates of normal (plateau) basalt. He shows how the excessive precipitation of olivine produces free silica in the residual liquid.[3] The Palisades sheet is taken to illustrate the process. Its quartz diabase has the character and position expected according to the theory. The initial magma is approximately indicated by the average analysis of the chill phase of the sheet and associated intrusions (column 2, Table 49). Columns 3 and 4 give the average compositions of the high-lying quartzose phase and of the low-lying layer of olivine diabase. Further study may yet remove one trouble with the theory as applied to the Palisades sheet: contrary to expectation the total of the iron oxides in the more siliceous phase is actually greater than in the chill phase.

[1] W. Wahl, Fennia, vol. 24, 1908, p. 69. J. A. Thomson, Proc. Roy. Soc. New South Wales, vol. 45, 1912, p. 311.

[2] D. Balsillie, Geol. Mag., vol. 59, 1922, p. 442.

[3] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, pp. 85, 91

A statistical review of the basalts, diabases, and quartz diabases all over the world leads to another question not satisfactorily answered by any published statement of the theory of crystal fractionation. Column 7 of Table 49 may be compared with columns 5 and 1. The British Guiana quartz diabase is one of several well analyzed that, like the world average for quartz diabase, contrast with average diabase or with average plateau basalt. The alkalies thus appear to be less abundant in some quartz diabases than in either of the other rock types. Yet Bowen's theory demands that the separation of olivine or any other likely mineral from primary basaltic liquid should raise the percentage of alkalies as well as silica in the residual liquid. Does this mean that averages are not proper data for an attack on the problem? Or do the world averages indicate that processes other than straightforward fractional crystallization have been at work?

TABLE 49.—QUARTZ DIABASE AND GRANOPHYRIC DIABASE
(Analyses calculated to water free and to totals of 100)

	1	2	3	4	5	6	7	8
Number of analyses averaged.	43	4	1	2	90	12	1	8
SiO_2.. . .	49 70	51 86	60 26	49 37	51 45	53.17	54.23	55.49
TiO_2........	2 23	1.26	1 74	1 00	1 48	1.85	1 49	1.29
Al_2O_3. .. .	14 24	14 72	11 92	10 33	15 64	13.92	13 25	16.90
Fe_2O_3......	3 66	2 83	3 24	1.09	3 91	5.13	4 26	2 48
FeO.........	9 96	8 22	10.24	11.25	7 93	8.92	10.00	6.93
MnO........	17	20	28	.12	.21	.23	21	.23
MgO.......	6.82	7.34	.85	16.64	5 90	4.79	5 03	4 84
CaO........	9 55	10.48	4 78	8 09	9.11	8.16	8 99	6.72
Na_2O........	2.64	2 28	4 06	1.50	3 13	2.64	1 79	3.09
K_2O.	.70	.66	2 11	.48	.98	1.19	.74	1.68
P_2O_5	.33	.15	.52	.13	26	....	.01	35

1. Average plateau basalt.
2. Average chill phase (Palisades sheet).
3. Quartz diabase (Palisades sheet).
4. Average olivine diabase (Palisades sheet).
5. Average diabase (world)
6. Average quartz diabase (world).
7. Quartz diabase (Demerara River, British Guiana).
8. Average quartz gabbro (world)

In this connection the results of a study by Collins on the Nipissing diabases of Ontario may be significant. There he found the non-quartzose part of the quartz diabase to have the composition of an "ordinary quartzless gabbro or diabase." Could straightforward crystal fractionation of basaltic liquid give such a relation? On its face Collins's conclusion suggests, rather, importation of much of the

more siliceous constituent from outside; it would then be a case of addition rather than subtraction.[1]

However, notwithstanding such apparent difficulties, Bowen's explanation of the rocks now being considered may yet be proved for many cases, to general satisfaction.

III. The old hypothesis that the micropegmatite of the quartz diabases was introduced by the secondary action of hot gases has been revived by Fenner but rejected by Bowen.[2]

IV. Another hypothesis looks to moderate contamination of normal basaltic magma by acid material. This will be discussed in the next chapter, where its probability for some quartz diabases will be affirmed, though crystal fractionation of the syntectic liquid may be assumed. Meanwhile we may note that this group of rocks may well be referred to several modes of origin, and it does not seem possible to reject any of the four modes above listed.

Norites

The intimacy of norite and olivine norite with gabbro in the field has been amply demonstrated. The norites are transitional into gabbro and olivine norite, on the one hand, and into mica-hypersthene diorite and quartz-mica-hypersthene diorite, on the other.[3] Average olivine-free norite has 1 per cent more silica than plateau basalt. Except for a higher percentage of alumina, olivine norite is chemically almost identical with average olivine diabase (compare columns 54, 60, 62, and 65 of Table 1). Olivine-free norite commonly holds accessory quartz, with or without some biotite or hornblende or both.

Consanguinity and transition are strikingly represented in each of the four thick masses of Insizwa, Tonti, Tabankulu, and Ingeli mountains of East Griqualand. There picrite passes upward with rather rapid transition into olivine gabbro and olivine norite, which, still farther up in each section, become charged with interstitial quartz, in micrographic intergrowth with alkaline feldspar. The chill phase at each floor is the normal Karroo dolerite, itself differing but slightly from average plateau basalt.[4]

The Bushveld Complex similarly illustrates the close bond between the various types of norite and diabase as well as quartz-bearing basic

[1] W. H. Collins, Econ. Geol., vol. 5, 1910, p. 545.

[2] C. N. Fenner, Jour. Geol., vol. 34, 1926, p. 753. N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 73.

[3] *Cf.* H. Rosenbusch, Mikroskopische Physiographie der Massigen Gesteine, 4th ed., Stuttgart, 1907, p. 348.

[4] See Nos. 27 to 30 of Table 40, with references; also A. L. du Toit, The Geology of South Africa, Edinburgh, 1926, p. 287.

species.[1] Another example is furnished by the big basic mass in Sierra Leone, described by Dixey.[2] According to Prior, the norites of coarse-grained enstatite dolerites of the Umqueme Range, Zululand, "might well be more deeply seated rocks derived from the same magma which supplies the dolerites" of the region.[3] Collins found the norite of a sill in the Onaping map area, Ontario, to be transitional into quartz diabase.[4] The norite of the Raana mass, Norway, passes into quartz norite.[5]

Quite moderate differentiation of basaltic magma that had been slightly contaminated appears to offer the most satisfactory explanation of most norites.

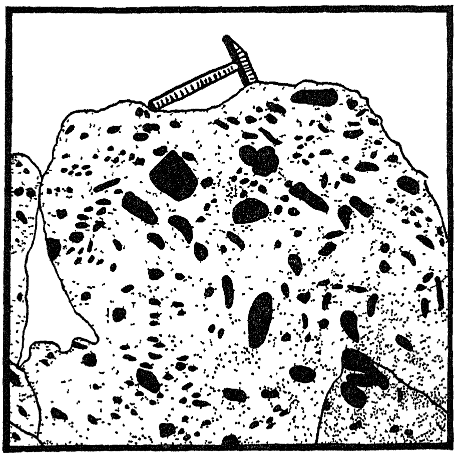

FIG. 138.—Sedimentary xenoliths (*black*) in garnetiferous norite at Castle Bridge, Huntly, Scotland. (*After H. H. Read, Geol. Mag., vol.* 61, 1924, *p.* 434.)

First, we note the special case of cordierite norite, interpreted by Lacroix, Winchell, Watt, Read, and others as a product of the absorption of aluminous sediments by basaltic liquid[6] (see Fig. 138).

[1] R. A. Daly, Bull. Geol. Soc. America, vol. 39, 1928, p. 703.

[2] F. Dixey, Quart. Jour. Geol. Soc. London, vol. 78, 1922, p. 299.

[3] G. T. Prior, Annals Natal Museum, vol. 2, 1910, p. 147.

[4] W. H. Collins, Mem. 95, Geol. Survey Canada, 1917, p. 87.

[5] S. Foslie, Jour. Geol. vol. 29, 1921, p. 701.

[6] A. Lacroix, Bull. serv. carte géol. France, vol. 10, 1898–1899, p. 341. A. N. Winchell, Amer. Geologist, vol. 26, 1900, p. 294. W. R. Watt, Quart. Jour. Geol. Soc., London, vol. 70, 1914, p. 282. H. H. Read, Geology of the Country round Banff, etc., Memoir Geol. Survey Scotland, 1923, p. 137. On page 114 of his memoir Read states his belief in the derivation of the Scottish norite from "a plain gabbro magma." *Cf.* C. E. Tilley, Geol. Mag., vol. 58, 1921, p. 560, and vol. 60, 1923, p. 418.

Bowen's study of the question led him to conclude: "The formation of norite and of pyroxenites characterized by orthopyroxene, as differentiates from basaltic magma, may therefore be facilitated by reaction of such magma with aluminous sediments." This statement is significant in connection with the problem of the norite, bronzitite, and allied differentiates of the Bushveld Complex, where large quantities of the shales of the Transvaal system seem to have disappeared after inclusion in the original basic magma.[1]

An effect in the same direction, but perhaps still more general, may be the absorption of silica by basaltic liquid, the reactions following the course outlined by Bowen.[2]

Presumably, hypersthene basalts and enstatite diabases have originated by processes similar to those responsible for the norites.

Hornblende Gabbros

Like the norites, many hornblende gabbros are poor in alkalies. For example, we glance at the composition of the dominant rock of the Purcell sills of British Columbia and Idaho in column 1 of the following table, which also (column 2) gives the approximate composition of the substratum basalt.

	1	2
SiO_2	52.94	48 5
TiO_2	73	2 6
Al_2O_3	14.22	13.8
Fe_2O_3	2.08	3.5
FeO	8.11	9.8
MnO	.35	.2
MgO	6.99	6.3
CaO	10.92	9.6
Na_2O	1.40	2.7
K_2O	.49	.9
H_2O	1.68	1.7
P_2O_5	.08	.4
	99.99	100 0

According to Schofield, the Purcell magma locally crystallized as a hypersthene gabbro, with a composition nearly like that of the basalt (column 2).[3] The sills and their feeding dikes cut quartzites and

[1] N. L. Bowen, Jour. Geol., vol. 30, Supp., 1922, p. 550. *Cf.* P. A. Wagner, Mem. 21, Geol. Survey South Africa, 1924, p. 33. H. H. Read (Geol. Mag., vol., 68, 1931, p. 453) remarks: "If there were not so many slates there would not be so many norites."

[2] Page 549 of the cited paper.

[3] S. J. Schofield, Museum Bull. 2, Geol. Survey Canada, 1914, p. 8. Schofield's insistence upon the secondary nature of the hornblende of the Purcell sills raises

metargillites of unusual thickness. The basic magma absorbed some of this sedimentary material and therewith water and other volatile substances (see page 429). The leaching action of these gases seems competent to explain the low alkaline content of the gabbro, and the destination of part of the migrating alkalies is apparent, for the hornfelses at the roofs of the Purcell sills are more or less alkalinized.

Resurgent water may also account for the poverty of the analogous quartz diabase in alkalies.[1]

Iron Basalt

Rosenbusch's handbook contains a discussion of the Greenland basalt carrying segregations charged with metallic iron. Törnebohm, Zirkel, and Schwantke all refer the metallic state of the iron to the reducing action of reacting carbonaceous matter, preferably from the bituminous sediments traversed by the basalt. The close field association of "graphite basalt" with the Greenland iron-bearing rocks, and also proof by Benedicks that the iron is a true steel, support that theory.[2]

Anorthosites

This name for rocks essentially composed of plagioclase was not a happy choice, but a better one has not yet been invented. "Plagioclase rock" would include the genetically different albitites and oligoclasites with the types made up of strongly calcic feldspar. Since the rocks meant to be covered include those with respectively dominant andesine and bytownite as well as labradorite, "labradorite rock" or "labradoritite" is too narrow.

Vogt discussed the chemistry of the group. He found the percentage of anorthite in the plagioclases to range from 40 to 85 (Ab_3An_2

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the question of the definition of terms. The author regards this amphibole as primary in the sense of being a deuteric product, formed by reaction at a late-magmatic stage of the crystallization, in the presence of the relatively abundant water of a rest magma.

[1] For an example see H. Backlund's description of the diabase of Kusjkin Island, Siberia (Mém. Acad. Imp. Sciences, St. Petersburg, vol. 21, 1910, p. 25).

[2] A. E. Törnebohm, Bihang Svenska Vet. Akad. Handl., vol. 5, 1878, p. 16. F. Zirkel, Lehrbuch der Petrographie, 2d ed., vol. 2, Leipzig, 1894, p. 894. A. Schwantke, Sitzungsber. Akad. Wiss., Berlin, vol. 50, 1906, p. 853. C. Benedicks, Compte Rendu Cong. Géol. Internat., 11th session, Stockholm, 1910 (1912), p. 885.

J. B. Tyrrell (Amer. Jour. Science, vol. 33, 1887, p. 73) described the formation of metallic iron from clay ironstone by the underground burning of lignite.

A. Osann in H. Rosenbusch, "Elemente der Gesteinslehre, 4th ed., Stuttgart, 1923, p. 428, describes other instances of native iron in basalt, including some in Germany, Bohemia, and Ireland.

to about Ab_1An_5), though usually the mixture lies between Ab_1An_1 and Ab_2An_3. In large masses of anorthosite the percentage of mafic constituents, generally pyroxenes and iron ore, varies from 2.5 to about 25, for the Sogn-Bergen rock averaging about 12 per cent. The potash feldspar in solid solution is 1 to 6 per cent of the plagioclase by weight.[1]

Special Characteristics.—The origin of the anorthosites is an outstanding problem. Its intrinsic importance and its bearing upon the fundamental principles of petrology warrant a summary of the main facts known about this group of rocks.

1. Although small bodies of anorthosite date from periods as late as the Tertiary, the greater masses appear to have been emplaced during the late Pre-Cambrian (see page 43). The fact is illustrated in Table 50, which lists the principal outcrops. It implies somewhat peculiar conditions obtaining in post-Archean and pre-Paleozoic time.

2. In contrast with most of the other plutonic species, no effusive equivalent of anorthosite has been found. This negative result of field work suggests on its face that the feldspar rock as such was never molten, for we might expect such a liquid to have broken its way to the earth's surface at some points.

3. The grain may be unusually coarse, the feldspars reaching lengths of 5 to 15 or more centimeters.

4. Most of the large bodies show pronounced effects of strain. Those of cataclastic, even mylonitic, nature were induced after crystallization of the material as a coherent rock. Protoclastic textures are common and are reasonably attributed to shearing of the feldspathic material while being lithified. We shall see that the rule is apparently not universal, some of the Transvaal, Minnesotan, and Norwegian anorthosites exhibiting practically no strain phenomena.[2]

5. The feldspar rocks and associated mafic phases tend to be strongly banded. The layers of anorthosite parallel others composed of pyroxenes, iron ore, chromite, and olivine in endlessly varied proportions among themselves as well as with basic plagioclase.

6. With rare exceptions, dikes and apophyses of typical anorthosite are unknown.

Genetic Association with Gabbro and Norite.—Nearly all special students of anorthosites believe them to be differentiates of gabbroic

[1] J. H. L. Vogt, Videns.-Skrifter, Oslo, Kl. I, 1924, No. 15, p. 52.

[2] J. H. L. Vogt (Videns.-Skrifter, Oslo, Kl. I, 1923, No. 17, p. 15) found the labradorite rock of Ekersund not to exhibit the protoclastic structure. The same is true of some phases of the typical anorthosite in the Bushveld Igneous Complex (R. A. Daly, Bull. Geol. Soc. America, vol. 39, 1928, p. 734).

TABLE 50.—LOCATION AND AGE OF ANORTHOSITIC BODIES

Region	Approximate area, square kilometers	Date of intrusion
Labrador peninsula (17 large bodies)	130,000	Pre-Cambrian
Saguenay district, Quebec	15,000	Pre-Cambrian
St. Urbain, Quebec	350	Pre-Cambrian
Morin district, Quebec	2,500	Pre-Cambrian
Ten smaller areas between Three Rivers and Montreal, Quebec	....	Pre-Cambrian
Kildare, Cathcart, and Brandon townships, Quebec (5 small bodies)	.....	Pre-Cambrian
Chibougamau, Quebec	250	Pre-Cambrian
Moisie River, Quebec	....	Pre-Cambrian
Georgian Bay, Ontario	......	Pre-Cambrian
Thunder Bay, Ontario (small body)	....	Pre-Cambrian
Rainy Lake district, Ontario	65	Pre-Cambrian
St. John, New Brunswick	....	?
Southern Vancouver Island (dikes and veins)	......	Post-Triassic
St. George's Bay, Newfoundland (area 95 km long)	......	?
Adirondacks, New York State	3,000	Pre-Cambrian
Northern New Jersey (small body)	....	?
North Carolina (small body)	....	?
Beaver Bay, Minnesota (small body)	....	Pre-Cambrian
Sherman quadrangle, Wyoming	125	Pre-Cambrian
Upper St. Joe River, Idaho	15	Pre-Cambrian (?)
Los Angeles County, California	......	?
Portsoy, Scotland (small body)	....	Pre-Cambrian (?)
Bergen district, Norway (3 small bodies)	10–150	Pre-Cambrian
Ekersund-Soggendal district, Norway	950	Pre-Cambrian
Voss-Sogn district, Norway	2,000	Pre-Cambrian
Lofoten Islands	....	?
Ångermanland, Sweden	....	Pre-Cambrian
Volhynia, Podolia, and Cherson districts (large massifs)	....	Pre-Cambrian
Island of Skye (local differentiates)	....	Tertiary
Island of Rum (local differentiates)	....	Tertiary
Ranigani district, India	....	Pre-Cambrian
Bushveld Complex, Transvaal (bands in norite)	....	Late Pre-Cambrian (?)
Natal-Zululand (phases of sills)	....	Jurassic
Volovolo River, Madagascar	1	?

magma or the closely related noritic magma.[1] In confirmation a few examples may be cited from the field.

[1] J. H. L. Vogt (Videns.-Skrifter, Oslo, Kl. I, 1924, No. 15, p. 89) took an exceptional view: "The parent magma of the anorthosites cannot differ very far from the average composition of the igneous rocks, given by Clarke and Washington."

Cooke demonstrated the case when describing a large Tertiary intrusion of gabbro in the East Sooke Peninsula, Vancouver Island. According to Prior, differentiation in place accounts for the anorthositic and pyroxenitic phases in sill dolerite cutting Permian beds of Natal and Zululand. Bowen regards the anorthosite within the Thunder Bay sills, Ontario, as a gravitative differentiate in place from

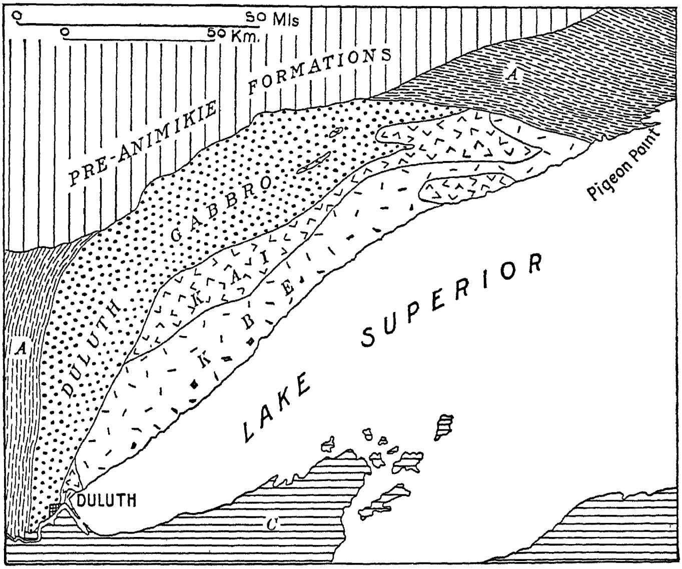


FIG. 139.—Map of the Duluth lopolith. *A*, Animikie slates etc.; *KBE*, Keweenawan "basic extrusive"; *KAI*, Keweenawan "acidic intrusive"; *C*, Cambrian and later sediments. (*After C. R. Van Hise and C. K. Leith, Mon.* 52, *U. S. Geol. Survey*, 1911.)

diabase magma. Grout adopts a similar explanation for anorthosite of Minnesota sills, intruded at about the same epoch. The Winchells had made a parallel deduction for the anorthosite of the dominantly gabbroic part of the Duluth lopolith (Fig. 139). Equally clear is the case for the lenses and long bands within the Bushveld noritic body.[1]

No convincing reason is given for this unorthodox belief. Probably no large body corresponding chemically with the "average composition" calculated by either Clarke or Washington ever existed, at least since the Sial was formed.

[1] H. C. Cooke, Museum Bull. 30, Geol. Survey Canada, 1919, p. 32. G. T. Prior, Annals Natal Museum, vol. 2, 1910, p. 147. N. L. Bowen, 20th Ann. Rep. Ontario Bur. Mines, 1911, p. 127. F. F. Grout, Bull. Geol. Soc. America, vol. 39, 1928, p. 562. N. H. Winchell, Final Rep. Geol. and Nat. Hist. Survey Minnesota, vol. 4, 1899, p. 302. N. H. Winchell and H. V. Winchell, Bull. 6 of the same Survey, 1891, p. 126. *Cf.* C. R. Van Hise and C. K. Leith, Mon. 52, U. S. Geol. Survey, 1911, p. 374. P. A. Wagner, Mem. 21, Geol. Survey South Africa, 1924, pp. 31, 63.

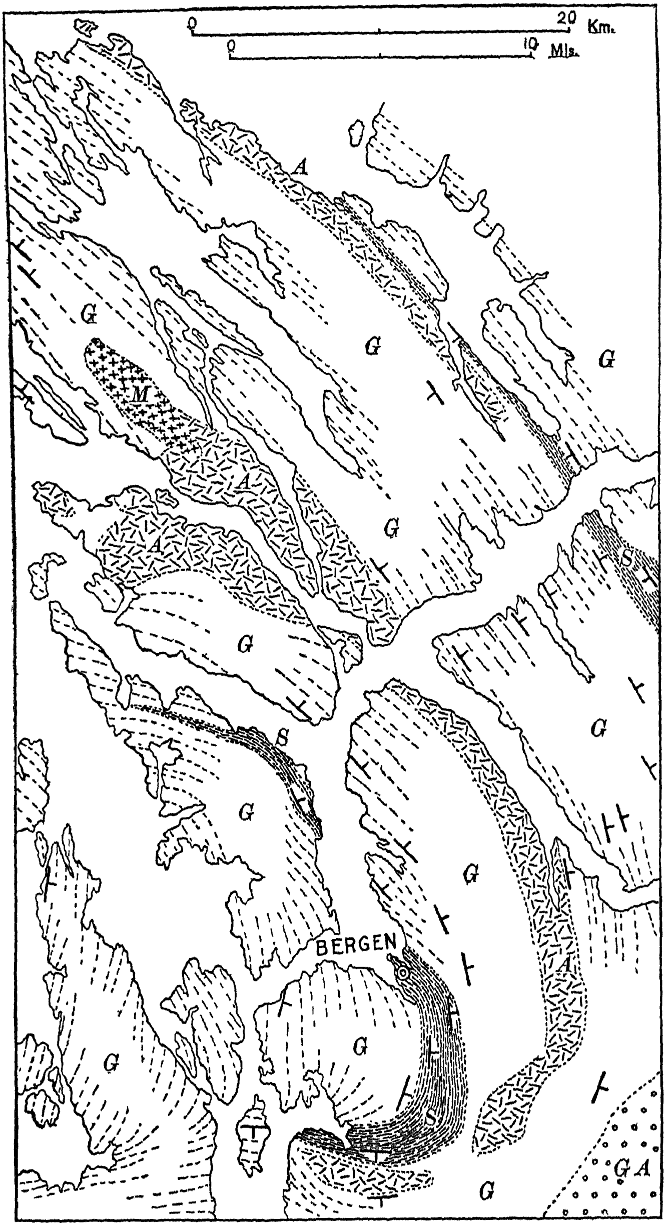


FIG. 140.—Map of anorthosite areas, Bergen district, Norway. *G*, gneiss and granite; *S*, Silurian rocks; *A*, anorthosite; *M*, mangerite; *GA*, saussurite gabbro. Symbols for strike and dip. (*After C. F. Kolderup, Bergens Museums Aarbog*, 1903, *No.* 12.)

Even in those cases where the feldspathic material, separated in depth, was moved and intruded at higher horizons, derivation from gabbroic or noritic magma has been convincingly argued by Geikie, Teall, Harker, and others.

Eruptive Form of the Original Magma.—The nature of the small, floored bodies mentioned above at once suggests an injected origin (floored chambers) for the masses from which the voluminous anorthosites were differentiated. For these the cover of rock was thick enough

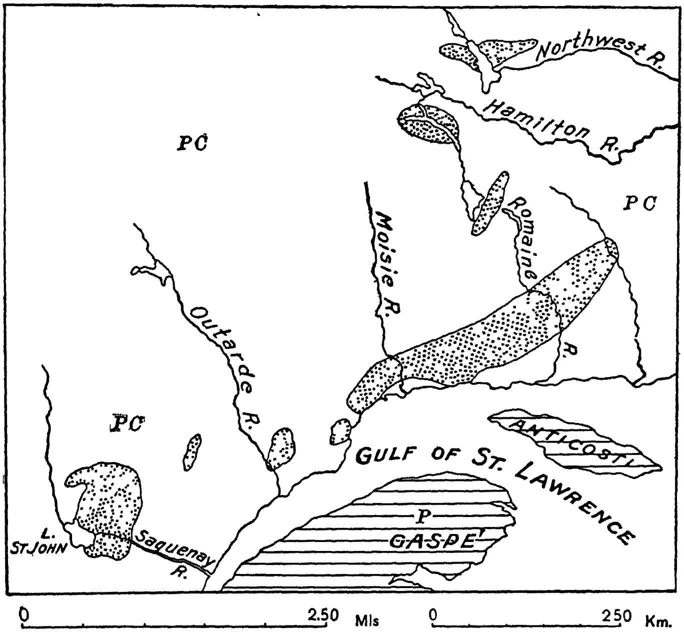


FIG. 141.—Map of anorthosite areas in eastern Canada. *PC*, Pre-Cambrian gneisses etc., *P*, Paleozoic formations; *dotted*, anorthosite. (*After Atlas of Canada, Interior Department, Ottawa,* 1906, *Plate* 5.)

to permit the "plutonic" texture. Another hint of injected character is given by the not uncommon association of anorthositic bodies with independent gabbroic laccoliths or sheets occurring in the same respective regions. Further, known laccoliths and lopoliths of gabbro have breadth of outcrop and probably thickness sufficient to account for the huge volumes of some anorthosites, if these were gravitative differentiates of thick gabbroic injections in place.

The feldspathic differentiates themselves have been displaced, to form separate intrusions, which also tend to be concordant with the layering of the country rocks. Illustrations are described in the memoirs on the Morin district of Quebec (Adams), the Bergen district

of Norway (Fig. 140), and Ångermanland, Sweden (Högbom).[1] Until more field data are secured, it is impossible to separate genetically and thoroughly those anorthosites that have been so displaced and injected from others with the relations of differentiates in place.

Such critical observations should be multiplied for the Saguenay and other anorthosites of Quebec (Fig. 141), for the Labrador bodies totaling 130,000 square kilometers in area (Adams), for the several Norwegian masses, and for those in Russia.

Meanwhile the author continues to entertain the hypothesis of injection (laccolith, sheet, lopolith, or harpolith) and floored condition for all the parent (gabbroic or noritic) bodies from which anorthosites were derived. Mere size is not an objection. The largest mapped mass, the Saguenay, is no broader than the Duluth gabbro lopolith. Sills, with extension smaller but of the same order, clearly indicate the possibility of major horizontal injections of greater thickness.

Mode of Differentiation.—There has been considerable discussion of this subject. Opinions differ on vital points. Bowen, Daly, Goldschmidt, Grout, Hall, Wagner, and others postulate gabbroic magma or the closely related noritic magma as the parent of anorthosite. Vogt alone preferred a dioritic or andesitic magma.

The segregation of the plagioclase is generally taken to have been gravitative, the solid crystals either rising (Beskow, Buddington, Goldschmidt, Grout, Loewinson-Lessing) or sinking (Bowen, Vogt).[2] In fact the relations of density are delicate. Crystals of acid plagioclase should rise in normal basaltic liquid but sink in the liquid resulting from only slight differentiation or contamination of normal basalt; while bytownite and anorthite would probably sink in either kind of liquid. According to Grout, the feldspar did rise toward the roofs of gabbroic sills in Minnesota. In any case plagioclase crystals are likely to rise in liquid a little more femic than plateau basalt.

The collection of labradorite crystals near the tops of the greater basic masses is suggested by the field relations. Thus the Chibougamau anorthosite, with an outcrop length of 45 kilometers and width of 8 kilometers, appears to overlie a syngenetic, complex layer of gabbro, basic norite, pyroxenite, and iron ore.[3] As not unexpected,

[1] F. D. Adams, Ann. Rep. Geol. Survey Canada, vol. 8, part J (map), 1895 (*cf.* Figs. 153 and 154 in "Igneous Rocks and Their Origin"); Jour. Geol., vol. 1, 1893, p. 334. A. G. Hogbom, Geol. Fören. Förh. Stockholm, vol. 31, 1909, p. 366.

[2] See G. Beskow's detailed paper, Sodra Storfjället im Südlichen Lappland, Avhand. Sver. Geol. Unders., ser. C, No. 350, 1929, p. 257, with references; also A. F. Buddington, Jour. Geol., vol. 39, 1931, p. 246, with references; and V. M. Goldschmidt, Videns.-Skrifter, Oslo, Kl. I, 1922, No. 10, p. 9.

[3] A. E. Barlow, J. C. Gwillim, and E. R. Faribault, Report on the Geology and Mineral Resources of the Chibougamau Region, Bur. Mines Quebec, 1911, p. 156.

several anorthositic masses pass into chill-contact phases of gabbroic rock. Illustrations, all indicating the probability of the differentiating process described, have been noted in the Morin district, Quebec; the Saguenay district, Quebec (Fig. 141); the Rainy Lake district, Ontario; the Adirondacks (Figs. 107 and 142); and the Ekersund-Soggendal district, Norway.

The question as to the stability of the segregated crystals of plagioclase has differing answers.

Bowen assumes no superheat for the parent magma and therefore doubts re-solution of the gravitatively displaced crystals. Collected

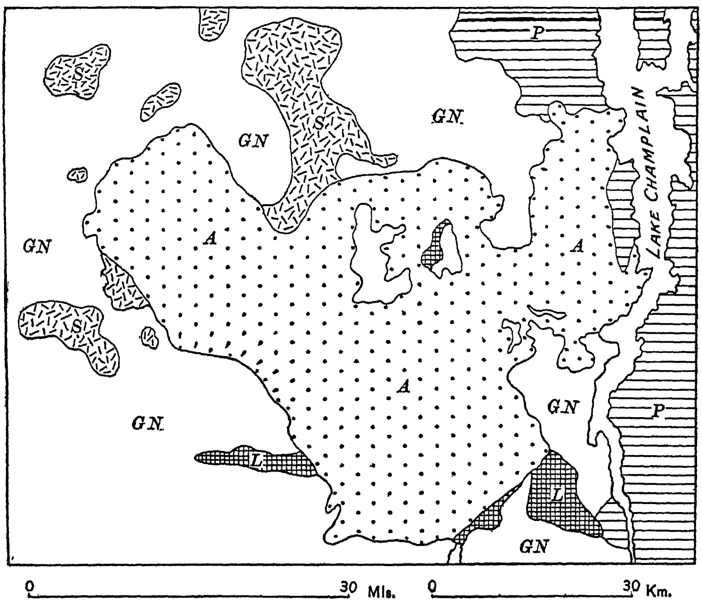


FIG. 142.—Map of anorthosite and syenite in the Adirondacks, New York State. *GN*, gneiss and granite; *L*, Grenville limestone and schists; *A*, anorthosite and gabbro; *S*, syenite; *P*, Paleozoic sediments (overlap). (*After wall map of State Geol. Survey.*)

together, these are subject to late-magmatic and post-magmatic shears and crushing, which account for the common protoclastic texture of the anorthosites and also for their apophysal injection into the country rocks. At no time molten, the anorthositic material cannot form narrow dikes or surface (volcanic) flows; nor should anorthosite exhibit the variation of grain characteristic of contact chilling. Hence several special features of many of these bodies of rock are automatically explained.

Mawdsley believes the more acid part of the anorthosite in the Saint Urbain district, Quebec, to have been liquid. This part is rather uniformly composed of andesine with small percentages of mafic

minerals. At many places it intrudes the associated phase, a typical labradorite rock.[1]

In Los Angeles County, California, Miller has found "numerous dikes of practically pure plagioclase anorthosite, ranging in width from a fraction of an inch to 75 or 100 feet and in length from a few inches to at least 100 feet." He regards the material as truly magmatic when emplaced.[2]

Similarly Vogt believed anorthosite to have been molten, repeated re-solution of sunken crystals of plagioclase giving ultimately liquid feldspar rock. He assumed great superheat at the deeper levels of each original magma, the initial temperature being of the order of 2000°C. So elevated a temperature is supposed to have characterized magma during that early period of the earth's history when all the bigger bodies of anorthosite were emplaced. Vogt regarded his hypothesis as supported by the discovery of contact chilling in the Ekersund anorthosite and of fine-grained anorthositic dikes in the Sogn region. He well knew that both criteria are seldom satisfied elsewhere and agreed that effusive anorthositic material is "completely missing," though this fact is not expected if each anorthositic body were at one time molten.[3]

To postulate an initial temperature approaching 2000° involves, as we have seen, new questions. A major intrusion of such magma could hardly fail to assimilate foreign acid rock to the extent of a large fraction of the magma's own weight. Would basic plagioclase be segregated in the observed quantity during or after the drastic contamination?

If, however, we could assume some superheat in the parent magma, we might be on the way to explain the common syngenesis of anorthosite with granitic or syenitic rocks. All three types seem to have been differentiated in a single magma chamber. Examples are (*a*) the Duluth lopolith and the Pigeon Point sill, (*b*) the Adirondack complex (Fig. 142) of gabbro, anorthosite, syenite, and granite, all of which locally grade into one another,[4] (*c*) the consanguineous group of anorthosites, norites, monzonites, and banatites of the Ekersund-Soggendal district of Norway, (*d*) similar assemblages in the Bergen district and the Lofoten Islands,[5] (*e*) the Bushveld Complex,

[1] J. B. Mawdsley, Mem. 152, Geol. Survey Canada, 1927, p. 18. N. L. Bowen (The Evolution of the Igneous Rocks, Princeton, 1928, p. 171) is not content with Mawdsley's evidence of liquidity.

[2] W. J. Miller, Abstracts of Papers, 44th Ann. Meeting of the Geol. Soc. America, 1931, p. 22.

[3] J. H. L. Vogt, Videns.-Skrifter, Oslo, Kl. I, 1924, No. 15, pp. 84, 97.

[4] H. P. Cushing, Bull. 115, New York State Museum, 1907, p. 477.

[5] C. F. Kolderup, Bergens Mus. Aarbog, 1896, No. 5, 1903, No. 12; 1898, No. 7.

(*f*) the gabbro-anorthosite-granite of the Sooke district, Vancouver Island, and (*g*) the rock group of Chibougamau.

The chapter on differentiation considers a cause for the separation of the feldspar rock from gabbroic or noritic magma (see page 354). According to the suggestion there made, the downshowering of plagioclase crystals in large quantity may have been due to special conditions, including intermittent convection and/or reaction between the original basic magma and the country rocks.

In summary, it appears probable (1) that in general anorthosites are gravitational segregations of plagioclase crystals in initially basaltic magma; (2) that the separation took place in large chambers of the floored type of injection; (3) that in part the visible masses of the feldspar rock were moved and intruded after their separation; (4) that anorthosites of large volumes were developed in late Pre-Cambrian time, when also gabbroic laccoliths, sheets, and lopoliths were injected into the crust on a big scale; (5) that some of the anorthosites were generated in chambers hot enough to permit some solution of foreign rock and perhaps some re-solution of sunken crystals of plagioclase; and (6) that no volcanic equivalent of anorthosite has been discovered, though the parent basaltic injections may have originated and fed volcanoes above their roofs during the hot stage before much of the plagioclase could be separated.

Pillow Basalts and the "Spilitic Suite"

The pillow lavas, ranging in age from the Pre-Cambrian to the present epoch, are either normal basalts or else types closely allied. Most of their special students regard them as subaqueous flows.[1] The reason for the balling-up of the lava into relatively small, completely separated pillows or ellipsoids is a physical problem of fascinating difficulty; the structure has been connected with the development of the "spheroidal state" at the contact of water and hot basic lava, but no one has made the matter clear.

These rocks won particular attention when Dewey and Flett concluded that "the pillow-lavas are members of a natural family of igneous suite, that can be clearly distinguished from the Atlantic and Pacific suites." Brongniart, who originated the term "spilite" (1827), regarded the rock as an albitized basalt. That opinion is still held by

[1] Among the many illustrations see L. D. Burling, Jour. Geol., vol. 24, 1916, p. 235; A. F. Buddington, *ibid.*, vol. 34, 1926, p. 824. H. S. Washington (personal communication) states that during the 1891 eruption at Pantelleria rounded pillows of lava floated up to the surface of the sea, as if directly from the top of a submarine flow. W. G. Foye (Bull. Geol. Soc. America, vol. 35, 1924, p. 329) doubts that the Triassic pillow lavas of Connecticut were erupted subaqueously. Possibly some pillow basalts were intruded into wet muds.

some investigators. For example, Sargent finds the secret in the autometamorphism (autolysis) of normal basalt; Eskola, after a useful review of the problem of albitization, finds it not "necessary to assume any inherent primary difference between the spilitic and the normal basaltic magmas"; and Rastall considers the introduction of the spilitic suite into petrography to be without justification. With this view Wells does not agree but suggests that basalt and spilite "have very possibly been derived from a common stock."[1]

The author shares the opinion of those (including Washington—personal communication) who recognize no good ground for separating a spilitic suite, to have even the degrees of definiteness and objectivity that characterize the "Atlantic" and "Pacific" suites. The typical spilites of Germany are intimately associated with ordinary basalts or diabases, and Dewey and Flett themselves admitted that all these rocks belong to one eruptive period. They explained the albitic character of the feldspar as the effect of pneumatolytic, "post-volcanic or juvenile changes of rock-masses." They did not discuss the idea that the abundant soda was concentrated from normal basaltic magma, replacing more calcic plagioclase in associated basaltic material; yet well-ascertained facts support this view, shared also by Beskow, who has ably summarized the situation. Some of those facts are recorded on page 339 of "Igneous Rocks and Their Origin," where was also indicated the possibility of significant albitization of basaltic rocks by resurgent water. Is it an accident that the spilitic pillow lavas so often show evidence of having been erupted through wet sediments, to solidify in the presence of abundant steam of foreign origin?

On the other hand, many of these albite-rich rocks are intrusive or in other structural relations that practically forbid us to assume any important gain of resurgent water from sediments at and close to the bottom of sea or lake. The common association with keratophyres and other acid, soda-rich types points in the same direction. The late-magmatic or deuteric ("autolytic," "pneumatolytic," "autometamorphic") development of the albite seems to demand a special abundance of volatile matter, particularly water and carbon dioxide. That abundance needs explanation, and it is difficult to discern the conditions under which purely juvenile vapor or gas could be concentrated, bringing the required soda and other oxides with it. If we postulate resurgence of the volatiles from depths well below the level

[1] H. Dewey and J. S. Flett, Geol. Mag., vol. 8, 1911, p. 245. H. C. Sargent, Nature, vol. 99, 1917, p. 59. P. Eskola, Fennia, vol. 45, No. 19, 1925, p. 91. R. H. Rastall, Physico-chemical Geology, London, 1927, p. 95. A. K. Wells, Geol. Mag., vol. 60, 1923, p. 71. For general discussions, see W. N. Benson, Proc. Linn. Soc. New South Wales, vol. 50, 1915, p. 157, and G. Beskow, Avhand. Sver. Geol. Unders., No. 350, 1929, p. 280.

of active sedimentation, the mystery is lessened. But there remains the more fundamental question as to the nature of the magma within which the concentration took place and led to the "primary" crystallization of albite and the associated albitization. In holding that typical spilites are deuteric products of ordinary basaltic magma, the author agrees with Eskola, who has given one of the best treatments of the subject, and does not "beg the question" (Wells) but offers again a speculative answer to it. Like some other writers, Backlund gives another speculative answer, calling the liquid wherein the soda and volatiles began to be concentrated an "original magma" (*Ursprungsmagma*) but makes no statement about its chemical nature; is this not the very crux of the matter?[1]

Conclusion

This chapter, like all that follow, illustrates the difficulty of discussing origins of species in detail. Each member of the gabbro clan represents a particular, and for the most part, new problem. Its full solution demands specific data concerning field relations, temperature conditions, the exact nature of the parent liquid, its possible contamination, the units of differentiation, the length of the magmatic life, and the character of the eruptive process, whether legato or staccato. Hence all suggestions of origin for individual varieties of igneous rocks are necessarily tentative and the treatment remains incomplete.

The species of the gabbro clan actually discussed are important in themselves and also because they seem to show the working of principles that affect the genesis of all other igneous species. If our general theory is correct, the causes for the chemical variation within the gabbro clan should be reflected in the much greater chemical range within the other clans, and from these to the gabbro clan we expect abundant evidence of transition. That both consequences accord with the facts is a principal thesis of the rest of this book.

[1] H. G. Backlund, Norske Videns.-Akad. Oslo, Rep. Norw. Exped. N. Zemlya, 1921, No. 45, 1930, p. 60.

CHAPTER XVII

GRANITE CLAN

INTRODUCTION

The origin of granite is to be sought in the depths of time as well as of space. Most of the visible granite was generated before the Archean complexes attained their essential structure. The later granites were evolved at levels generally too deep for direct observation. The whole problem is therefore eminently one for speculation. Fortunately the imaginative range is somewhat limited by the facts of geophysics and geology. These suggest some broad conclusions about the genesis of the granites and their hypabyssal and effusive equivalents. To some extent the effort to visualize the mightier events is aided by study of exposed eruptive bodies. Although of relatively small size and thermal content, certain of the injected masses illustrate the processes that have controlled magmatic happenings in the depths of the hot earth. Appearing to be true homologies and to exhibit a mechanism like that which governed the development of the earth shells, they show "which way the wind blows." Before considering this side of the complex subject, it may be helpful to summarize the relevant ideas of previous chapters.

RETROSPECT. GENERAL THEORY OF THE SIAL AND ABYSSOLITHIC GRANITE

The assumption of former liquidity for the earth is in line with prevailing cosmogonic theory and seems actually necessary if we are to understand the internal structure of the globe. Lively convection in the outer part of the young earth is supposed to have given a superficial, liquid, iron-rich shell of comparatively homogeneous composition. By crystal fractionation (less probably by unmixing of liquids) this shell is assumed to have become divided into two layers: one rich in silica, largely granitic, and from 15 to 20 kilometers thick (the primitive Sial); the other underlying, more femic and much thicker. The upper part of the lower layer attained the composition of plateau basalt, faintly stratified according to density. In the course of time all of the Sial and some of the basaltic sublayer became crystallized, to form a true crust. This was thicker and more Simatic beneath the primitive ocean, and it looks as if these contrasts with the suboceanic

and continental parts of the crust were accentuated in late Archean time.

However, the primitive Sial is not thought to have been developed in a single act. It was the integrated product of many crustings, founderings, and remeltings, which continued even after a felsic layer of some thickness had already been developed at the earth's surface.[1] Anatexis and palingenesis, aided by waves of heat and gas rising from the interior of the young planet, facilitated the differentiation and caused extensive displacements of the salic magmas. Thus numberless lenses, sills, laccoliths, lopoliths, and dikes were injected into the upper part of the new Sialic crust. In addition, large bottomless masses of granite (batholiths) seem to have been generated by anatexis (Lawson, Michel-Lévy, Sederholm, Fenner, and others).

Although periodic eruptions of basaltic magma were common during the Archean era, the regional invasion of the upper part of the crust by granitic liquid does not appear to have always required the preliminary rise of basic magma, nor, according to the theory of palingenesis, should this have been necessary.

Essentially different have been the conditions for the origination and rise of voluminous granitic magmas during late Archean and all subsequent time. Great intrusions of these younger salic liquids were confined to the orogenic belts; palingenesis near the earth's surface and on the continental scale is not represented. Usually the intrusion of post-Archean granite was preceded by abyssolithic injection of basic magma, the granite being a late term in the normal eruptive sequence, from basic to acid. All around each post-Archean massif of granite the earth's crust has kept considerable thickness. Hence, in general, the formation of the massif involved abyssal injection, the preliminary rise of substratum basalt into the crust.

Chapter X contains a revised statement of the theory of abyssal injection as affected by the assumption of continental migration to the extent of at least a few tens of kilometers. Both the crust-sliding and crust-dragging hypotheses of mountain building imply major downwarps and founderings of the Sial, into the substratum, and similar displacements are reasonable deductions from the contraction theory itself. At equal pace the vitreous basalt rises (is injected), to take the place of the sinking Sialic rocks. The mountain roots are thus at first invaded by basaltic magma, and here and there small volumes of this melt escape through the writhing, sheared, compressed rocks of the mountain structure. After a considerable time the deeply sunken blocks and slabs of Sialic rock are actually melted by the heat of the

[1] If, as seems highly probable, the thermal gradient was considerably steeper than it is now, remelting of large volumes of sunken rocks would be inevitable.

substratum. This *abyssal* palingenesis is accompanied by some solution of Sialic rock in the hot basalt.

Although the dominant rocks at the surface of the Basement Complex are granites, there are associated many smaller bodies of granodiorite, tonalite, and other intermediate types as well as more basic eruptives, both intrusive and extrusive. Below a moderate depth the proportion of basic rocks in the Sialic mixture doubtless increases with depth, and, apart from the enhancing of density by metamorphism, the mean density of the Sial, especially its lower half, is a condition for the major stoping assumed. The abyssal melting and solution of the heterogeneous, sunken blocks and downwarped Sial give secondary melts of variable composition. While ranging from dioritic or tonalitic through granodioritic to granitic, each of these melts is less dense than the substratum basalt and therefore, because the time allowed is too short for complete diffusion into the basalt, however miscible, the secondary magma rises through the basalt all the way to the roots of the overlying mountains. There the liquid basalt of the great initial injection sinks beneath the lighter magma, which accumulates under the thinnest parts of the new mountain structure of the solid crust.

The masses of invading, relatively salic magma are crosscutting and, of course, bottomless from the start. As major abyssoliths they stope and replace some roof rock, causing further moderate rise of the liquids into the mountain roots, and the typical relations of the visible batholiths are established. If the abyssal-palingenetic magma is initially granitic, it retains that composition until it crystallizes, high in the mountain structure. If the invading magma is more femic—granodioritic, for example—it freezes as such or it may undergo differentiation with the development of granite or quartz monzonite at the roof of the new abyssolith.

The explanation of mountain chains through horizontal displacement of the Sial (whether caused by the motion of independent blocks, or by elastic expansion according to the contraction theory) thus leads to a picture of granitic massifs different from that described in "Igneous Rocks and Their Origin." Each of the vital processes, abyssal injection, magmatic stoping and replacement, and abyssal remelting and solution of Sialic rock with gravitational self-cleansing of the substratum and its thicker offshoots, is now imagined to be on a still grander scale.

Richardson, like Bowen, does not approve of this conception of what may be called a double origin for the granites of the world, but to assume a single mode of origin is to plunge into difficulties.[1]

[1] W. A. Richardson, Geol. Mag., vol. 60, 1923, p. 123. N. L. Bowen, Jour. Geol., vol. 23, Supp., 1915, p. 69. Concerning this general subject see the paper by A. Holmes, Geol. Mag., vol. 69, 1932, p. 546.

In illustration we recall Bowen's description of all granitic magma as liquid residual from the fractional crystallization of plateau basalt. If his hypothesis be applied to the primitive Sial (already nearly or quite full-bodied in early Archean time), we must assume an enormous concentration of basic material below the Sial. It is impossible to believe that the material there could retain the chemical character of plateau basalt, that is, the liquid supposed by Bowen to be the parent of post-Cambrian granite. The composition of the primitive sub-Sial layer would approach that of a peridotite. Some geophysicists would not object to this deduction, for they hold that the Sial now rests directly upon a thick peridotitic shell or is separated from it by only a thin layer. On the other hand, no geologist who knows the facts about eruptive sequences can be satisfied with that theory of the earth's constitution. Nor can it content the geophysicist himself if he tries to account adequately for major facts of observation—the great volume and world-wide distribution of post-Archean basaltic rocks.[1]

If the granite of a typical post-Archean batholith represents the residual liquid from basaltic magma, the volume of this parent must have been colossal, with a horizontal extension at least as great as that of the visible batholith and with thickness measurable in tens or scores of kilometers. Bowen appreciates the situation; when he accounts for "parental" basaltic liquid by partial remelting of the peridotite, he virtually postulates a local substratum of vitreous basalt. Thus he avoids the difficulty of imagining how a basaltic liquid voluminous enough to yield a batholithic granite can find room in an earth exteriorly composed of crystalline Sial resting directly upon crystalline peridotite. Nevertheless, Bowen's hypothesis has trouble of its own. The required concentration of mafic minerals below the visible granite should there give the crust—within which, by hypothesis, the differentiation takes place—an abnormally high density. Many batholiths projecting high above the mean level of the continental surface should, therefore, be sites of an excessive pull of gravity. The fact is that there is no such excess.

Our problem seems much less obscure if we assume many post-Archean batholiths to be really abyssoliths bearing correspondingly large supplies of heat from the earth's interior. The thermal energy of the bodies cannot be so readily understood if they were floored with solid rock from the beginning. Clear it is that part of the Archean

[1] In connection with Bowen's theory of granite and effusive obsidians, is there significance in the results of E. S. Shepherd, his colleague at the Geophysical Laboratory of Washington (Ann. Rep. Director 1931, p. 82), that at least some obsidians are unexpectedly free from concentrations of those rarer elements which might be expected in a residual mother liquor?

granite was emplaced by pure injection as lenses, dikes, phacoliths, etc. The principle of the economy of postulates would of itself prompt the hypothesis that all other intrusions of granite are pure injections. In reality, some even large crosscutting bodies of granite, both Archean and younger, were passively intruded among crust blocks when these were moved about during orogenic paroxysms. The fluidal and protoclastic textures of these chonoliths and harpoliths prove high viscosity and also solid plasticity during the final emplacements. With great wealth of detail, Cloos and his school proved the powerful shearing of several important granites of Central Europe as these were freezing. Excellent parallels are found in many separate bodies of the "porphyritic granite" (Meredith granite) and Chatham granite of the State of New Hampshire. These American masses were pinched, displaced, and visibly injected as they crystallized. More than thirty years ago, the author studied the extraordinarily clear case of the Meredith granite with some care and fully appreciated the contemporaneity of the mountain building and the final emplacement of the granite.[1]

Yet intrusions of this type are not likely to shed much light on the origin of their salic magmas. To discuss the question intelligently we need to know the location and nature of the parent chamber from which the visible granite was moved during the orogenic shearing of the crust. As noted on an earlier page, the problem is much more than that of the *final* emplacement of the bodies, the *finishing* of a long process. The hope of solving the problem seems better founded if particular stress is laid upon the abundant batholithic granites that were emplaced after orogenic shearing of the crust had been essentially completed. That these, when liquid, were connected directly and freely with the basaltic substratum is, of course, not now to be proved, and perhaps geological science can never hope to develop any method of proof or disproof. The treatment of the matter must long remain frankly speculative. Yet, if we do assume such one-time, wide, and free connection of the visible batholith with the earth's interior, the thermal requirements can be met in theory. No alternative hypothesis now published seems as competent to account for the heat of the massifs and for their relations to the rest of the earth's crust.

This explanation of the granites has some points of resemblance with that recently outlined by Eskola. He also assumes the primitive development of granitic masses from initially basic liquid and the formation of some batholiths, Pre-Cambrian and younger, by abyssal remelting. However, Eskola has

[1] R. A. Daly, Jour. Geol., vol. 5, 1897, p. 794. *Cf.* M. P. Billings, Proc. Amer. Acad. Arts and Sciences, vol. 63, 1928, p. 83.

. . . become more and more impressed with the idea that granitic magmas must have been formed in connection with orogenic movements by the pressing out or squeezing of the lowest melting materials, partly from more basic rocks not yet entirely solidified and partly from rocks partially re-fused in the deep regions of the geosynclines.

The main source of the granitic liquid is assumed to be a 23-kilometer layer transitional between the overlying holocrystalline Sima and the holovitreous Sima, that intermediate earth shell being itself largely crystallized Sima but containing "pores" filled with salic residual liquid. Orogenic squeezing and assembling of these "pore" solutions are supposed to generate granitic liquids of batholithic dimensions.

Eskola so pictures the earth shells resulting from the secular crystallization of the original Simatic layer of liquid, because he assumes a difference of 700° between the temperature at which basalt begins to crystallize and that where the "last granitic residual magma crystallizes" (1300° to 600°). Vogt made this difference about 250° only (1250° to *ca.* 1000°) and evidently regarded the low temperatures approaching 600° as controlled by migration and concentration of volatiles to an extent not to be expected in the pores of a freezing basaltic liquid. It does seem doubtful that the salic residual of basalt is sufficiently charged with non-imported volatiles to remain liquid much below 1000°. In fact, Goranson found that granite with as much as 3 per cent water was not wholly molten until the temperature of about 1020° was reached (see page 68). Granite containing the normal amount of volatiles begins to melt a little below 600°, but the material then becoming liquid is not granite. Diabase begins to melt at 1150° (see page 66), the interstitial or last crystallizing part not behaving like granite when heated from 600° to 1150°. Is it, then, just to assume that the thickness of the "pore"-bearing shell which is to yield granite by squeezing covers the entire zone of temperature in the crust between 600° and 1300°?

Moreover, Eskola has not allowed for the greater effect of pressure on the melting temperature of granite as compared with the effect in the case of basalt. From the data of Chapter V it appears possible that these effects are in the ratio of about 2:1.

For two reasons, therefore, the transitional layer is probably much thinner than the 23-kilometer layer assumed by Eskola—perhaps no more than 5 kilometers thick.

In any case the query is justified as to whether the transitional layer can have the volume required to furnish the impressive bodies of batholithic granite intruded during any petrogenetic cycle.

Eskola repeatedly emphasizes the rise of light liquids because of their relative density; he nowhere mentions downstoping as a possi-

bility, though the density of the fully crystallized layer, like that of the pore-bearing layer, must be decidedly greater than that of the vitreous shell beneath. He does assume as probable the pure melting (selective fusion included) and assimilation of orogenically depressed rocks, but seems not to believe in any loss of solid-elastic connection of such mountain roots with the rest of the earth's crust. Here is one of the principal distinctions between Eskola's theory and the author's.[1]

Harker seems to have well realized that the residual liquid of freezing basalt is not granitic when he proposed an explanation of unsaturated feldspathoidal and other alkali-rich rocks by a wine-press mechanism essentially identical with that assumed by Eskola for the generation of the supersaturated granite (see page 488). While Harker's hypothesis appears less troubled by the physical chemistry of the situation, it, like Eskola's, has yet to be correlated with a workable theory of orogenesis.

Evidence from Injected Bodies

Speculation about granitic batholiths may well be guided by analogy. More objective and distinctly illuminating are the facts ascertained concerning small bodies of the injected type, sills, laccoliths, chonoliths, and dikes. Granites and granophyres are found in the appropriate syngenetic relation to basaltic magma, that otherwise constituted thick injections with exposed roofs and floors. These bodies usually exhibit gravitative differentiation, the granitic phase overlying the basaltic (gabbroid or diabasic) phase, transition between those phases, and, in some instances, definite evidence of a secondary origin for at least some of the material constituting the quartzose phase, whether by pure melting or through assimilation by the basaltic liquid. Each injection represents a kind of experiment in petrogenesis. Each well-exposed chamber is a crucible which can be examined from top to bottom and, because of its small volume, permits useful inference as to large-scale processes in depth.

Granite Derived from Syntectics of Sediments and Basaltic Magma

Purcell Sills.—The Purcell sills cut Beltian (late Pre-Cambrian) beds on both sides of the boundary between British Columbia and Idaho, the invasion taking place just after the deposition of these

[1] P. Eskola, Min. u. Petr. Mitt., vol. 42, 1932, pp. 456, 468. On p. 458 it is stated that post-Cambrian granitic masses are mainly sheet-shaped, the Pre-Cambrian masses being bottomless, "batholithic." The author would just reverse this conclusion so far as post-Cambrian granitic masses are to be compared with the *visible* early Archean granites, which the author, like Högbom, Geijer, and others, regard as dominantly concordant masses (lit-par-lit sheets, etc.).

sediments. Then the beds were doubtless richer in connate water than they are now and were only partly lithified. Later they became hard quartzites and micaceous, somewhat feldspathic metargillites. One group of the sills, ranging in thickness from 30 meters to about 450 meters, is well exposed where the Moyie River crosses the Inter-

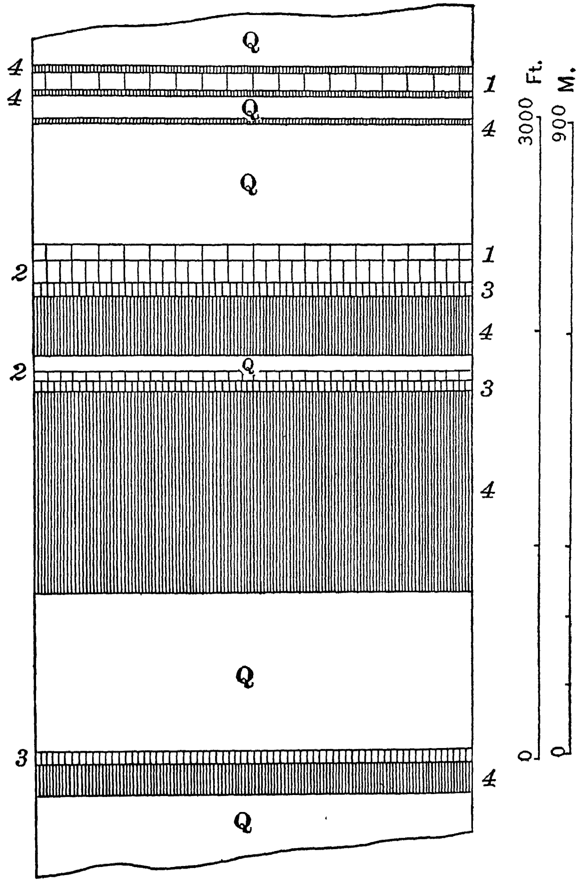


FIG. 143.—Section of differentiated sills, Moyie River, British Columbia. *Q*, quartzite and metargillite; *1*, biotite granite; *2*, hornblende-biotite granite; *3*, intermediate rock; *4*, gabbro. Five sills shown. (*After R. A. Daly, Memoir* 38, *Geol. Survey Canada*, 1912, *p.* 248.)

national Boundary. They illustrate gravitative differentiation with clearness (Fig. 143). In each of several instances the sheet exhibits a biotite granite (rarely hornblendic), passing downward through a more hornblendic phase into hornblende gabbro. Chemically the granites and gabbro are abnormal to a moderate degree.

At the upper contact of one of the thicker sills the quartzite is intensely metamorphosed. While the bedding is preserved, the now

massive sediment has field habit and microscopic character markedly like those of the sill granite. In both, micropegmatite is abundant. The evidence of "consanguinity" between the granite and quartzite was increased by the results of chemical study, results which seem particularly trustworthy because of the comparative homogeneity of the Beltian beds at this locality. The conclusion was reached that the abnormal granite had separated from a syntectic of the sediment with the basic liquid of the sill, originally gabbroic or basaltic.

The assimilation or pure melting was not confined to the sill chambers actually occupied by the granite. This is manifest in the case of those sills that are composed of little or nothing else than granite. Such bodies are best interpreted as offshoots from the thicker sheets where the preliminary differentiation took place. The displacement of the more siliceous phase, probably aided by the tension of resurgent water vapor, is in fact proved by the presence of some granitic dikes sent into the roofs of the differentiated sills. The chemical abnormality of the gabbro, even in the thin undifferentiated sills, suggests contamination by the sediments underlying the lowest of the visible injections. This would have been possible if the rise of the magma were of the staccato or step-by-step kind. How far syntexis with the crystalline rocks unconformably underlying the Beltian system was concerned in the magmatic history can hardly be guessed with profit.[1]

[1] For a detailed account of the Moyie sills, see Mem. 38, Geol Survey Canada, 1912, pp. 221–255.

S. J. Schofield (Museum Bull. 2, Geol. Survey Canada, 1914) believes "that little or no assimilation" was involved in the development of the abnormal granite of the Moyie sills, unless that reaction took place at levels below the visible sills. However, he has not adequately considered the evident consanguinity between the granite and the Beltian sediments, thus leaving Hamlet out of the play.

Quite in contrast F. von Wolff (Handbuch der Geophysik, ed. by B. Gutenberg, Berlin, vol. 3, Lief. 1, 1930, p. 122) regards the Moyie sill granite as "melted and recrystallized" quartzite. This view faces a difficulty in the higher content of the alkalies in the granite, which, if secondary, must have won some of that oxide material from the gabbroic liquid. Von Wolff thus overestimates the consanguinity between sediment and granite almost as much as Schofield underestimates it.

Both of these writers assume assimilation, if important in this case, to have depended necessarily upon magmatic stoping. The ground of their supposition is not apparent. In the author's original report (p. 247) he expressly recognized "various loci of solution in the sill [magma], namely, at roof and floor, at xenolithic contacts, and in the feeding channels below the sills."

Von Wolff finally decides that the Moyie sills actually give definite evidence against the assimilation, melting-up, (Aufschmelzung) and stoping hypotheses in general. He offers no logical reason for this remarkable decision.

Calkins describes two other differentiated sills of the Purcell assemblage, south of the International Boundary. He attributes the more siliceous phases to contamination of basic magma by the quartzose sediments intruded.[1]

Minnesota Cases.—The well-known sill at Pigeon Point, Minnesota, is a striking parallel (Figs. 144 and 145). Its gabbro is over-

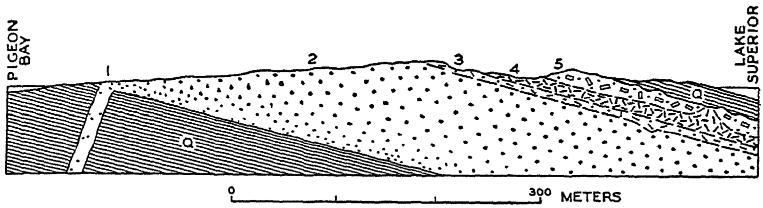


FIG. 144.—North-south section across the Pigeon Point sill. *Q*, Animikie quartzite and metargillite; *1*, chilled gabbro at base of sill; *2*, gabbro; *3*, intermediate rock; *4*, granite (micropegmatite); *5*, chilled upper gabbro with anorthositic segregations. (*After F. F. Grout, Bull. Geol. Soc. America, vol.* 39, 1928, *p.* 559.)

lain by micropegmatitic granite (granophyre), which Bayley, basing his conclusion on unusually thorough study, interpreted as due to the fusion of slate and quartzite in the original gabbroic magma. After independent investigation in the field Lawson stated his full agreement. In 1916, the present writer, aided by Professor C. Palache,

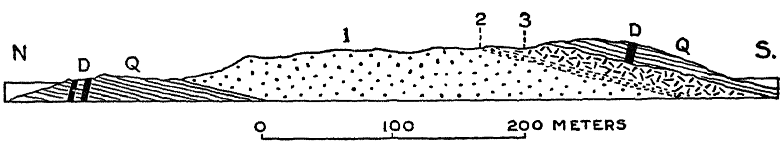


FIG. 145.—Dip section of the Pigeon Point sill, illustrating gravitative differentiation. *Q*, quartzite with interbeds of metargillite; *D*, diabase and gabbro dikes; *1*, gabbro; *2*, intermediate rock; *3*, red rock (granite). (*R. A. Daly, Amer. Jour. Science, vol.* 43, 1917, *p.* 429.)

mapped the sill and found no reason to doubt the secondary origin of the acid rock, though it was found that differentiation of the syntectic makes a condition preventing easy, straightforward demonstration. Recently Grout has revised the mapping, for the Geological Survey of Minnesota. He too accepts at least some assimilation of the invaded quartzitic sediments by the primary gabbro magma but prefers to think that differentiation was the "main control," the differentiated

[1] F. C. Calkins, Bull. 384, U.S. Geol. Survey, 1909, pp. 48–50. *Cf.* J. T. Pardee, Bull. 470, *ibid.*, 1911, p. 47; V. R. D. Kirkham and E. W. Ellis, Bull. 10, Idaho Bur. Mines, 1926, p. 36; S. J. Schofield, Summ. Rep. Geol. Survey Canada, 1910, p. 131. Another analogy, a differentiated sill near Marysville, Montana, was described by J. Barrell (Prof. Paper 57, U.S. Geol. Survey, 1907, p. 48).

material being originally "average diabase magma." He writes: "Not over one-fourth of the granite, and probably less, is due directly or indirectly to the assimilation of material from the sedimentary roof." No proof of this statement is given. It goes almost without saying that, if the syntexis hypothesis does here apply, a fraction of the material in the granite was derived from the gabbro magma.[1]

Similar relations obtain in the gigantic Duluth lopolith, of which the Pigeon Point sill may be an apophysis (see Fig. 139). The lopolith cuts Upper Huronian slates and more siliceous sediments, as well as the Lower Huronian and the pre-Huronian complex. The Duluth gabbro is capped by masses of "red rocks," granites, syenites, etc., long ago explained by Norwood and Winchell as products of the solution of the sediments by the gabbroic melt. The lavas on top of the granular "red rock" are chemically the same as the rocks of the lopolith.[2] Compare also the East Duluth sill (Table 40, No. 13).

Interformational Sheet at Sudbury, Ontario.—According to Coleman, this body represents a case of gravitative differentiation: a thick layer of micropegmatite (granite and granodiorite) passes downward into a thick layer of hornblende gabbro or "norite" (Figs. 146 and 147). The matrix and fine-grained parts of the so-called Trout Lake conglomerate, heavily metamorphosed at the roof of the injection, have marked resemblance to the micropegmatite; accordingly it is not always easy to map their mutual contact with certainty. Nevertheless, the author's own studies of the sheet incline him to doubt that much of the material of the acid phase was derived by assimilation from roof or floor. More probable is syntexis of quartzose rocks below the floor.

After detailed work Phemister questions the Coleman theory of differentiation in place and believes the micropegmatite and norite to be two separate intrusions.

> Relatively little time elapsed between the two intrusions, as is seen in the absence of a distinct contact phase of the micropegmatite against the "norite" in the majority of cases. . . . In the case of the "norite" the first effect of intrusion has been to produce a finer grained phase at the base. Following this, slight differentiation, probably gravitative, took place and produced a mesostasis of quartz and feldspar towards the top of the mass. . . . Following

[1] W. S. Bayley, Bull. 109, U.S. Geol. Survey, 1893. A. C. Lawson, Bull. 8, Geol. and Nat. Hist. Survey Minnesota, 1893, pp. 30, 31, 44. F. F. Grout, Bull. Geol. Soc. America, vol. 39, 1928, p. 555.

[2] N. H. Winchell, Final Rep. Geol. and Nat. Hist. Survey Minnesota, vol. 5, 1900, p. 978. *Cf.* vol. 4, 1899, plates 66–69; also Mon. 52, U.S. Geol. Survey, 1911, p. 377 and large map in pocket.

closely on the solidification of the "norite" came the intrusion of the micropegmatite while the "norite" was still hot.[1]

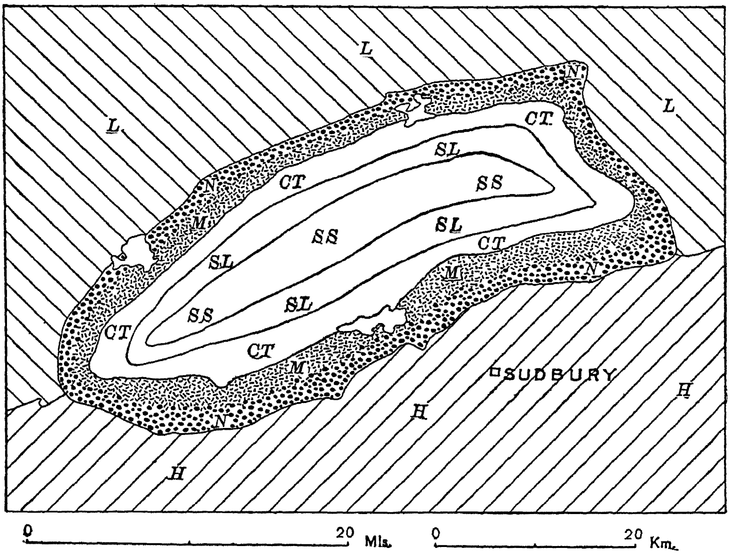


FIG. 146.—Map of the basined, interformational intrusive sheet at Sudbury, Ontario. *L*, Laurentian gneiss and granite; *H*, Huronian slate, greenstone, etc.; *CT*, Trout Lake conglomerate and Onaping tuff; *SL*, Onwatin slate; *SS*, Chelmsford sandstone; *N*, norite, and *M*, micropegmatite, of sheet. (*After A. P. Coleman, Rep. Bureau Mines Ontario, vol.* 14, 1905.)

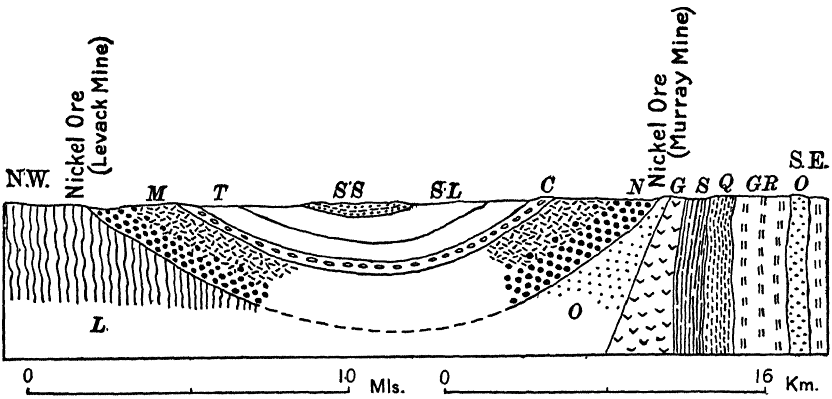


FIG. 147.—Section of sheet shown in Fig. 146. *Q*, quartzite; *GR*, graywacke; *S*, greenstone schist, *O*, older norite; *G*, granite; *C*, Trout Lake conglomerate; *T*, Onaping tuff. (*After A. P. Coleman, Jour. Geol., vol.* 15, 1907, *p.* 763.)

Yet Phemister's arguments for a two-stage intrusion may be questioned. As a rule the two types of rock grade into each other, though rapidly, and the gabbro is almost throughout characterized by a mesostasis that is quite similar in composition to the micropegmatite of the upper

[1] T. C. Phemister, 34th Ann. Rep. Ontario Bur. Mines, part 8, 1925, p. 26.

phase. Local sharp contacts of gabbro and micropegmatite are readily explicable as the results of shearing movements within the slowly cooling sheet as its floor was basined. According to Coleman, the sheet was warped into a spoon shape during or immediately after the intrusion. The salic and femic fractions of the magma may well have been so rearranged that the ratio between the volumes of the two phases was quite different from the ratio of the outcrop areas. This principle has weight in connection with quantitative discussion of both differentiation and assimilation, here as elsewhere. On the whole it seems clear that Coleman's theory of the Sudbury sheet is well founded.[1]

South African Cases.—Table 40 (Nos. 25 to 31) lists South African analogies. Du Toit points out that the Mesozoic Insizwa, Tabankulu, Tonti, and Ingeli masses, all enriched with micropegmatite in their upper levels, may be podlike thickenings of a single sheet, the connections among the pods having been destroyed by erosion. All of the bodies clearly illustrate differentiation in place, but the precise role of syntexis is uncertain, though there is evidence of some solution of the invaded sediments by the gabbroic magma. Rogers and du Toit remark on the abundance of small veins of quartz-orthoclase rocks cutting the dolerite sheets of the same—Karroo—system and note the difficulty of distinguishing this siliceous material from the metamorphosed sediments adjacent.[2]

Medford Dike.—The magma of a wide diabase dike at Medford, Massachusetts, reacted with quartz and quartzite xenoliths, a quartz-microcline micropegmatite resulting. The dike contains also irregular lenses of quartz-microcline pegmatite which merges into the normal diabase. Evidently differentiation tended to mask assimilation; yet the fact of corrosion, here as at many other localities, is manifest.[3]

Globe District Intrusions.—The intrusive diabase of the Globe district, Arizona, contains quartzose inclusions which "are conspicuously corroded and embayed."[4] The diabase forms thick sills, chonoliths, and dikes cutting thick limestones with acid sediments and basic schists. The differentiate of the average hybrid liquid, if assumed in this instance, should not be expected to be a highly quartzose rock or granite. As a matter of fact, the larger diabase masses

[1] A. P. Coleman, Jour. Geol., vol. 15, 1907, p. 759. A. P. Coleman, E. S. Moore, and T. L. Walker, The Sudbury Nickel Intrusive, Univ. Toronto Geol. Studies, No. 28, 1929.

[2] A. W Rogers and A. L. du Toit, 13th Ann. Rep. Geol. Comm. Cape of Good Hope, 1908, p. 105. *Cf.* 15th Ann. Rep., 1910, p. 9, and 16th Ann. Rep., 1912, p. 102.

[3] T. A. Jaggar, Amer. Geol., vol. 21, 1898, p. 203.

[4] F. L. Ransome, Globe folio, U.S. Geol. Survey, 1904, p. 8.

carry true syenitic phases, interpreted in the field as local facies of the diabasic magma.[1]

Swedish Cases.

In the southernmost part of Sweden one Jotnian area only occurs, the so-called "Almesåkra" group, S. E. from the southern end of Lake Wettern. This group is composed of white and red quartzites, felspar-bearing sandstones and arkoses, chocolate-brown shales and, more subordinately, conglomeratic layers and red calcareous sandstones. Dikes and beds of diabase are very abundant. They are remarkable by the intense contact influence exercised on the quartz-rocks, many times resulting in micrographic quartz-diabases and other rock-varieties of abnormal composition, as is described by Hedström. Fragments of the intruded rocks have also been more or less affected by the diabase magma.[2]

Högbom describes modifications of olivine diabase in sills cutting sandstone and granite of Ångermanland. Near its contacts the diabase loses olivine and becomes a quartz diabase with micrographic structure. Hybrid rocks were produced at the contact of the diabase and the older granite, and veins of granite (red in color as usual in these circumstances) traversing the diabase are interpreted by Högbom as felsic segregations of the acidified diabase.[3]

Scottish Intrusions.—According to Tyrrell, the injected quartz diabases of the Kilsyth-Croy district of Scotland "owe their origin to the interaction of a normal basalt magma with a highly siliceous country rock." He notes that

> . . . the mode of occurrence of this rock [micropegmatitic diabase or gabbro] is also distinctive. It always occurs in thick massive, vertical-sided dykes, which sometimes continue for many score miles across country, and also as thick laccolitic protrusions from such dykes.[4]

Tyrrell's generalization of considerable volume for each of these intrusive bodies applies elsewhere and is significant. Only in the larger injections of basaltic magma should notable amounts of siliceous country rocks be absorbed or should advanced differentiation be normally expected.

According to Stecher, the quartz diabases of the Firth of Forth region owe their free silica to solution of acid rock in diabasic liquid. He described the corrosion of quartzose inclusions and quoted Geikie's opinion that siliceous xenoliths had actually been dissolved in these

[1] F. L. Ransome, Prof. Paper 12, U.S. Geol. Survey, 1903, p. 85.

[2] A. G. Högbom, Bull. Geol. Inst. Upsala, vol. 10, 1909, p. 9; *cf.* H. Hedström, Blad 5, Ser. A1a, med Beskrifning, Sver. Geol. Unders., 1906.

[3] A. G. Högbom, Geol. Fören. Förh. Stockholm, vol. 31, 1909, pp. 369–370.

[4] G. W. Tyrrell, Geol. Mag., vol. 6, 1909, pp. 363–365.

sheet magmas. Stecher also recalled Schröder's similar conclusion regarding the absorption of granite by diabasic magma in Saxony.[1]

Read reports many examples of assimilation in Banffshire and Aberdeenshire, Scotland; among them is the case of the Insch mass of gabbro which has locally absorbed sedimentary gneiss, with the generation of biotite, quartz, and micropegmatite, all regarded as evidences of the contamination.[2]

Conclusion.—Thus sills and other injected bodies that can be studied from floor to roof seem to illustrate leading principles of the favored theory of post-Archean granites in general: syngenesis with basaltic liquid, the dominance of gravity in granitic differentiation, and commonly some preliminary syntexis of basaltic liquid and felsic rock, the granitic differentiate occasionally showing consanguinity with the latter. However, this conclusion should not be taken to imply the same genetic history for all granophyric or micropegmatitic rocks. We have already (page 200) seen reason to retain the working hypothesis of Wahl and others, that rocks of this kind, so abundantly developed during the late Pre-Cambrian are differentiates of, or eruptions from, a general earth shell of relatively acid basalt, then existing below the crust. Nor, in spite of its difficulties, should we summarily reject Bowen's conception of granophyre and micropegmatite as the material normally representing the liquid residual after the advanced crystallization of ordinary basalt. Either hypothesis involving pure differentiation, perhaps better than that involving syntexis, is qualified to explain the even distribution of the micropegmatitic mesostasis in so many quartz diabases and analogous rocks. In brief, quartz diabases and associated granophyres appear to have had more than one mode of origin.

Syntexis of Non-sedimentary Acid Rocks

The granitic differentiates so far cited are found in basic injections cutting siliceous sediments. The connate water of these facilitates both syntexis and differentiation. Yet neither sedimentary composition nor resurgent water is necessary in these processes. Gavelin described "magnificent remelting and assimilation phenomena" at the contact of gabbro cutting the Loftahammar granite of Sweden. There quartz gabbro, diorite, and regenerated, micropegmatitic granite were developed. One is reminded of the intimate association of granitic and diabasic rocks in the wide Brefven (Breven) dike, south of Lake

[1] E. Stecher, Tschermak's Min. und Petr. Mitt., vol. 9, 1888, p. 193.

[2] H. H. Read, The Geology of the Country round Banff, etc., Memoir Geol. Survey Scotland, 1923, p. 135.

Hjälmaren, Sweden, which cuts acid crystalline formations (Fig. 19).[1] Moberg explained the micropegmatite, biotite, and orthoclase in the olivine diabase of the Blekinge district, Sweden, by absorption of country-rock gneiss.[2] The diabase on Onega Lake is reported to have absorbed granite, with the generation of micropegmatite to the extent of 20 per cent of the resulting rock; and a similar effect was wrought in Siberian diabase cutting acid sediments.[3]

According to Mennell, some of the Matopo granite of Rhodesia was dissolved in the wide doleritic dikes of the region. He writes of "splendid examples" of the process, and of there being "every gradation" between the granophyres in the dikes and an "obvious mixed rock." He holds the common association of granophyre with gabbro or dolerite to be due to "admixture of acid and basic materials before intrusions." From the Natal dolerites Prior has described a "hybrid rock," collected by Anderson who labeled the specimen "basalt which has absorbed granite"; among the essential constituents are biotite, augite, and micropegmatite.[4]

Granitic Phases of Minor Abyssoliths

Narrow basaltic dikes, unless feeders to voluminous flows or injections, are speedily chilled to temperature too low for significant syntexis or differentiation. Wide basaltic dikes may show the results of both processes. Being of abyssolithic character, they necessarily make contact at depth with acid rock already at high temperature. From great depth the hot juvenile gases probably diffuse upward, and these also would tend to promote assimilation and differentiation. Where the erosion surface cuts the dike, the expected arrangement of rock types is as follows: at the walls, a chill phase composed of basaltic material or its more or less acidified representative; in the middle of the dike, a more siliceous phase corresponding to those so often found near the roofs of differentiated sills. The two phases should be transitional into each other, though the acid, longer fluid phase may be moved so as locally to cut, or make sharp contact with, the more

[1] A. Gavelin, Geol. Fören. Förh. Stockholm, 1910, p. 999. P. J. Holmquist, Bull. Geol. Inst. Upsala, vol. 7, 1906, p. 107. A. G. Högbom, Sver. Geol. Unders., ser. C, No. 182, 1899, p. 11, and Bull. Geol. Inst. Upsula, vol. 10, 1910, p. 18. K. Winge, Geol. Fören. Förh. Stockholm, vol. 18, 1896, p. 187.

[2] See reference in Rosenbusch's handbook, 4th ed., Stuttgart, 1908, p. 1250.

[3] D. Beljankin, Matér. Comm. Étude Répub. Jakoute, Livr. 23, Leningrad, 1927.

[4] J. P. Mennell, Geol. Mag., vol. 8, 1911, p. 10; Quart. Jour. Geol. Soc. London, vol. 66, 1910, p. 372. G. T. Prior, Annals Natal Museum, vol. 2, 1910, p. 150.

basic marginal phase. By the concentration of gas the former may have pegmatitic or aplitic habit.

A special problem arises in connection with the dikes feeding large fissure eruptions of basalt. These channels are characteristically narrow and yet their walls were more or less intensely heated and perhaps dissolved during the passage of the large volume of liquid. Was such syntexis responsible for the abundance of free quartz and micropegmatite in the dikes that fed the Eocene fissure eruptions of central part of the State of Washington—also for the quartz basalt that appears exceptionally among the Eocene (Teanaway) extrusive lavas of the same region (Fig. 57)?[1] The feeders of the Cuddapah trap flows, southeastern India, are likewise more siliceous than the extrusive traps and vary from norite, through diorite, to micropegmatitic granite.[2]

Granitic Differentiates in the Bushveld Complex

The Bushveld magma broke through to the earth's surface with such volume that the bulk of the visible eruptives of the complex may be regarded as a composite lava-flow (Figs. 90 and 90*a*). Initially the complex measured about 500 kilometers in length and nearly half that in width. The maximum thickness is unknown (it may be bottomless at or near the center), probably exceeding 10 kilometers. From the top downward the "flow" is composed of clearly effusive, rhyolitic felsite, granophyre and coarse red granite, intrusive norite with its own many phases of differentiation, and a well-developed chill phase of diabasic norite at the floor.

Elsewhere the author has summarized the evidence of Hall, du Toit, Wagner, and others in favor of assuming some absorption of the quartzites and shales that were overwhelmed and inclosed by the Bushveld magma. Probably much of the material of the salic differentiate did not originate in that way. The observed products of syntexis are such as to warrant the hypothesis that a large fraction of the salic material was derived from the depths, below the floor of the complex, through pure melting or assimilation of the Sialic rocks by hot basaltic magma. This speculation seems best to account for the relations of the various phases.

The youngest member of the complex, a coarse granite of pink color, cuts and breeciates the norite and is truly plutonic. It is possibly the

[1] G. O. Smith, Mount Stuart folio, U.S. Geol. Survey, 1904; G. O. Smith and F. C. Calkins, Snoqualmie folio, *ibid.*, 1906.

[2] T. H. Holland, Quart. Jour. Geol. Soc. London, vol. 53, 1897, p. 405. L. L. Fermor (Rec. Geol. Survey India, vol. 34, 1906, p. 148) regards the rhyolitic lavas, found locally among the Deccan basalts, as consanguineous with these, both being differentiates of the same magma.

product of the pure melting of the Sialic rocks at depth, after these had been basined, strongly depressed, under the inimitable "lava flow."[1]

Thus the Bushveld Complex conceivably illustrates on a big scale all of the major principles of petrogenesis, including abyssal injection of substratum basalt, pure melting, assimilation, and (dominantly gravitative) differentiation.

A sheet at the Elands River (locally roofless?) is well differentiated, with rhyolite above. In some respects it is a small replica of the Bushveld norite-granophyre-felsite mass and, indeed, may be an offshoot from the same generating chamber.

Another analogy may be an association of rocks cropping out along the Assegai River, Transvaal. There "a thick body of altered gabbro is found passing up into granophyre and that into amygdaloid without a break."[2]

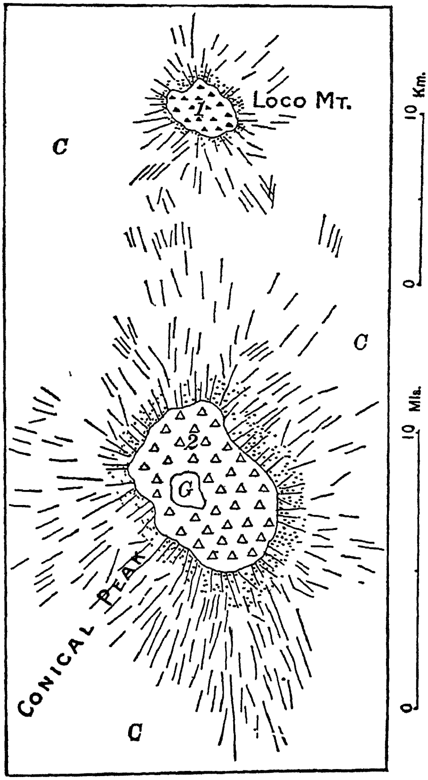


FIG. 148.—Map of intrusive stocks in the Crazy Mountains, Montana. *C*, Cretaceous sediments; *1*, Eocene diorite; *2*, Eocene quartz diorite; *G*, Eocene granite. Dikes shown by *lines;* contact aureoles *stippled.* (*After Little Belt Mountains folio, U. S. Geol. Survey*, 1899.)

GRANITE IN COMPOSITE SUBJACENT MASSES

The solidification of most large post-Archean batholiths is not a continuous process. In many a case, even at the limited depth exposed by erosion, we see that a large volume of a more basic phase crystallized at or near the batholithic roof or wall. This phase, still hot, was attacked and replaced by more salic liquid, evidently formed deeper in the same chamber. The differentiation of the attacking liquid was doubtless facilitated by juvenile and resurgent gases, which also increased the power of the liquid to replace the roof phase. In spite of the difficulty of explaining the fracturing of the hot rock, it seems best to believe that some of the replacement was due to piecemeal

[1] R. A. Daly, Bull. Geol. Soc. America, vol. 39, 1928, p. 765.

[2] A. L. du Toit, Geology of South Africa, Edinburgh, 1926, p. 32.

stoping. Marginal corrosion of the more mafic phase may also be important in accounting for its tendency to irregular outcrop.

Examples of dioritic phases of the type described have been noted in Chapter XIV. Another is illustrated in Fig. 148. The same mechanism may be reasonably ascribed to a common association of satellitic stocks of diorite alongside of larger stock or batholith of granite (Fig. 149). More speculative would be an application of the principle to account for the assemblage of diorite porphyrite sills and

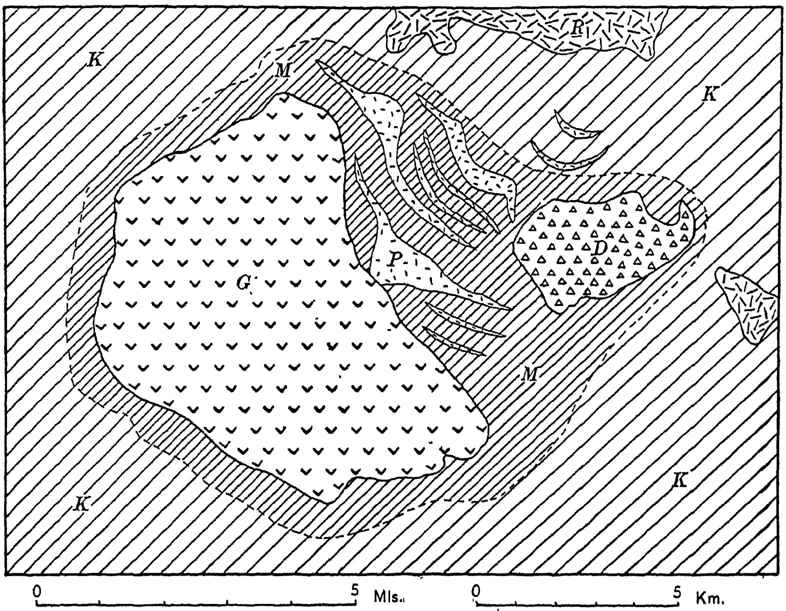


FIG 149.—Map of intrusive stocks in the Castle Mountains, Montana. *K*, Mesozoic sediments; *M*, metamorphic aureole; *D*, Neocene diorite; *G*, Neocene granite; *P*, Neocene rhyolite porphyry; *R*, Neocene rhyolite. (Same reference as for Fig. 148.)

laccoliths and granite porphyry and quartz-monzonite porphyry stocks and apophyses of stocks mapped in the Clifton quadrangle, Arizona.[1] An analogous, presumably abyssolithic syngenesis of granite and another member of the diorite clan, andesite, seems indicated by the geological and petrographical relations of these rocks in the Cheviot Hills (Fig. 150). The granite stock cuts the andesite, as if the latter was an earlier roof phase of the magma in a common batholithic chamber.

The Similkameen granodiorite (with granitic, monzonitic, and dioritic phases) of the Cascade Mountains is cut and partly replaced by the Cathedral granite, itself cut by a more felsic but closely allied

[1] W. Lindgren, Clifton folio, U.S. Geol. Survey, 1905.

granite having the apparent form of a huge dike. Microscopic and chemical evidence corroborates the field conclusion that these bodies are all parts of one batholithic mass. Thus the granites here are taken to be differentiates of a granodioritic liquid. The Skagit composite batholith, farther west in British Columbia, is a parallel case.[1] Many

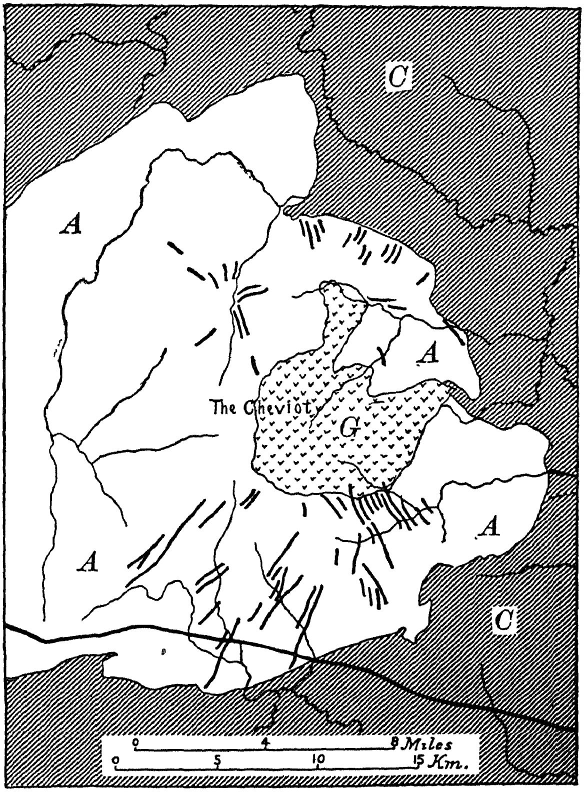


FIG. 150.—Map of the Cheviot district, England-Scotland. *C*, Carboniferous sediments; *A*, andesites; *G*, granite. Dikes shown by lines. The granite is interpreted as a late differentiate of the andesite magma (Kynaston). (*After H. Kynaston, Trans. Edinburgh Geol. Soc., vol.* 7, 1899, *p.* 390.)

others have been mapped in the Cordillera, for example by the authors of the Sierra Nevada folios of the United States Geological Survey.

What may be an actual example of differentiation in place occurs at the contact of the Trail batholith, near Rossland, British Columbia. There the intrusive rock is a granite porphyry, full of vogesitic segrega-

[1] R. A. Daly, Mem. 38, Geol. Survey Canada, 1912, pp. 455–464, 470–478, and 534–540; compare p. 785, where are listed other instances of the peripheral relation of diorite to batholithic diorite and granodiorite.

tions reaching 30 centimeters or more in diameter. These appear to be mafic masses "frozen in" by the salic liquid simultaneously developed during the local differentiation of the granodioritic magma.[1] Eskola has described an analogous case at Sviatoy Noss, where a composite

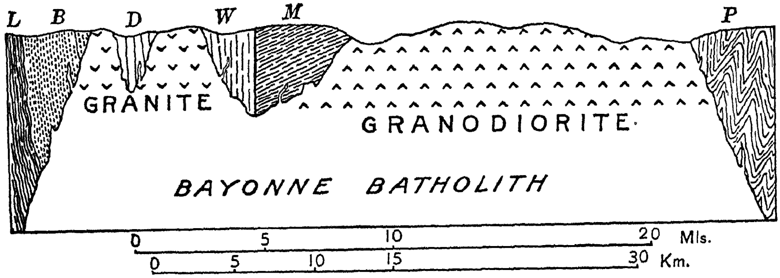


FIG. 151.—Section of the Bayonne batholith, British Columbia, showing relation between the dominant granodiorite and satellitic granite (cupolas). *P*, Priest River terrane; *M*, Monk argillite etc.; *W*, Wolf grit; *D*, Dewdney quartzite; *B*, Beehive quartzite; *L*. Lone star schist. (*After R. A. Daly, Mem*, 38, *Geol Survey Canada*, 1912, *p*. 302.)

dike of aplite and kersantite is taken to be the diaschistic product of a granodioritic liquid.[2]

Some satellitic stocks are less mafic than their neighboring parent batholiths. For example, the extensive Bayonne batholith of southern

TABLE 51*

Region	Earlier intrusion	Later intrusion
Monzoni	Monzonite	Granite
Predazzo	Monzonite	Granite
Aar massif	Syenite	Hornblende and biotite granites
Christiania	Alkaline syenite	Granite
Ekersund-Soggendal	Monzonite	Granite
Bergen	Mangerite, monzonite, soda-syenite	Granite
Thousand Islands, New York State	Alkaline syenite	Alkaline granite
Adirondacks	Syenite	Granite
Port Coldwell	Syenite	Granite

* References to the original memoirs are given on p 367 of "Igneous Rocks and Their Origin."

British Columbia is largely granodioritic, while the adjacent, evidently syngenetic, stocks are composed of the more acid biotite granite (Fig. 151). In part this difference of composition may be explained by the fact that the outcrops of the granite are close to the levels of the roofs of the stocks, while the batholith has been eroded to a relatively greater

[1] R. A. Daly, Mem. 38, Geol. Survey Canada, 1912, p. 348.

[2] P. Eskola, Finska Vetens.-Soc. Förh., vol. 63, Afd. A, No. 1, 1920–1921, p. 33.

depth. Perhaps, however, the granite appears in these stocks because differentiation was particularly advanced through the collection of gas at and near the roofs of the cupolas. The eruptives cut sediments of great thickness, so that the fluxing gas may have been resurgent to an important extent.[1]

The syngenesis of many granites and syenites is manifest. Here also the granite is usually the younger intrusion, as illustrated, for example, at Mount Ascutney, Vermont (Fig. 96). Other associations of the kind are listed in Table 51. By theory, continued syntexis of highly siliceous rocks in depth would, of course, give granitic liquids independent of an earlier syenitic phase.

Granitic Aplites and Pegmatites

Harker has well stated the process by which these subordinate phases of batholithic magma have probably been developed.[2] They

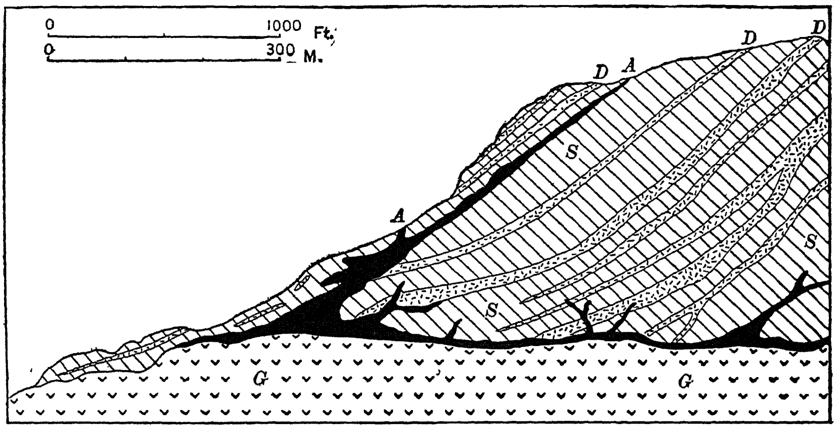


Fig. 152.—Section of Nickel Plate Mountain, Hedley district, British Columbia, illustrating the segregation of aplitic material at the roof of a batholith. *S*, Paleozoic sediments; *D*, sheets of diorite porphyry; *G*, granodiorite; *A* (*solid black*), aplite. (*After C. Camsell, Memoir 2, Geol. Survey Canada*, 1910, *p.* 101.)

have crystallized from gas-charged residual liquids. Both aplite and pegmatite form parts of the same dike or sill, as if in the first case volatiles had escaped and in the second case retained until crystallization was far advanced.

In some instances, simple gravity seems to have cooperated with filter pressing in the differentiation. An illustration is found in the Hedley district, British Columbia (Fig. 152), where the aplite was

[1] R. A. Daly, Mem. 38, Geol. Survey Canada, 1912, p. 301.

[2] A. Harker, The Natural History of the Igneous Rocks, New York, 1909, pp. 293, 323. N. Sundius (Arsbok 19, Sver. Geol. Unders., No. 3, 1925) specially discusses the separation of soda-rich and potash-rich phases of aplites and aplitic granites.

derived from granodioritic magma; another is in the Elkhorn district, Montana (Fig. 153). The roof apophyses of the Monzoni granite carry 76 per cent silica, while the normal rock has 70 to 71 per cent.[1]

However, Lane explains some pegmatites by "selective solution."[2] During intense regional or other metamorphism, deep-seated quartzose rocks reach the relatively low temperature at which a quasi-eutectic solution of quartz, feldspar, and some volatile matter is formed. Such small, locally generated pockets of fluid may be driven through

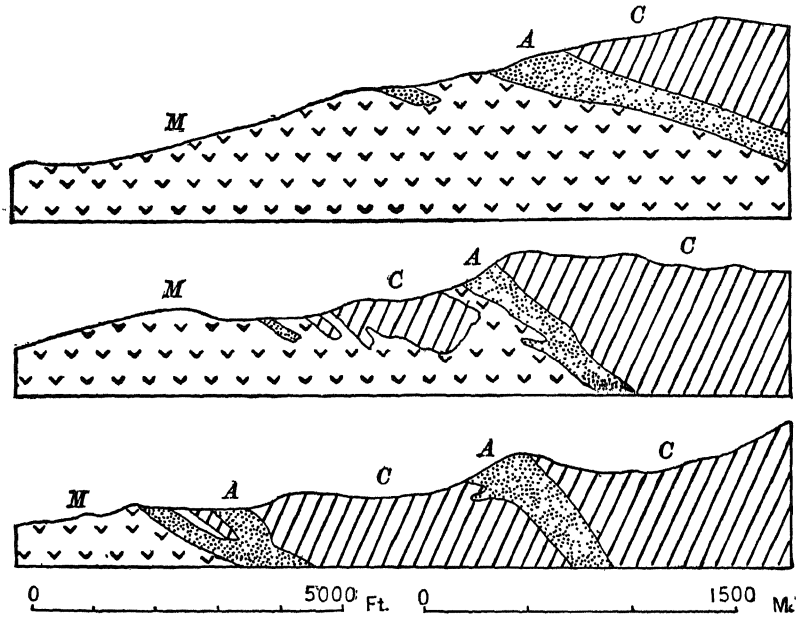


FIG. 153.—Sections in the Elkhorn mining district, Montana. C, country rocks; M, quartz monzonite and granite; A, aplite, collected at the roof of the batholith. (*After W. H. Weed*, 22d *Ann. Rep. U. S. Geol. Survey*, *Part* 2, 1901, *p.* 444.)

the surrounding solid rock as lenses or tongues which ultimately crystallize with the composition and habit of batholithic derivatives; though truly magmatic, the tongues have had no direct connection with primary magma.

RHYOLITIC TYPES

The rather systematic chemical difference between a volcanic type and its plutonic equivalent is most striking in the case of the granite clan (see columns 4 to 7 and 10 to 11, Table 1). In view of the large sizes of granitic chambers, this fact is not surprising. Granitic

[1] O. von Huber, Jahrb. k. k. Geol. Reichsanstalt, vol. 50, 1901, p. 395.
[2] A. C. Lane, Bull. Geol. Soc. America, vol. 24, 1913, p. 704.

magmas have long magmatic life, both because of their volumes and because of their relatively low temperature of consolidation. Differentiation should, therefore, be specially well advanced. The "cotectic" rhyolite is the abundant salic pole, and in general we may well regard gravity as the direct force engaged in its separation. The most salic phase, being concentrated near the roof of stock or batholith, is the most likely to be tapped for volcanic extrusion. Its formation, like that of granite, is held to be the result of pure melting, assimilation, and differentiation in varying proportion and at different stages in the history of deep-seated chambers. Eruption at central vents reflects these complicated conditions and commonly delivers to the earth's surface rhyolitic, dacitic, andesitic, and basaltic flows in more or less pronounced alternation.

A remarkable sequence of the kind, not yet published, has been kindly listed by Professor E. S. Larsen as the result of work done in the San Juan Mountains of Colorado:

Eocene: Andesites with some rhyolites.
Miocene:
- Series A.
  1. Andesite.
  2. Rhyolite.
  3. Latite.
  4. Pyroxene andesite.
- Series B.
  1. Andesite.
  2. Rhyolite and quartz latite.
  3. Andesite.
  4. Rhyolite.
  5. Quartz latite.
  6. Andesite.
  7. Rhyolite.
  8. Andesite.
  9. Quartz latite.
- Series C. Andesite and quartz latite.

Pliocene (?):
1. Andesite and quartz latite.
2. Rhyolite.
3. Basalt and andesite.
4. Andesite, quartz latite, and basalt.

Quaternary: Basalt.

Many other examples of the association are recorded in Appendix B of "Igneous Rocks and Their Origin."

The syngenetic relation of rhyolite to more femic magma is further shown by dikes and other small bodies. Judd's account of the

composite dikes of Arran is in point. The Cir Mohr dike is composed of two contact phases of "augite andesite" (tholeiite) inclosing a felsitic phase, itself inclosing a central phase of pitchstone porphyry. Tyrrell has since supplied good analyses of tholeiite and pitchstone constituting another of these Arran dikes.[1]

Soda liparites, comendites, and quartz keratophyres seem for the most part to have been generated in volcanic pipes and their individual bodies are all comparatively small. Why these types should be "alkaline" is a question to be considered, in principle, on later pages; for the present it may suffice to note the hypothesis that looks most promising. According to this, special abundance or concentration of gases, both resurgent and juvenile, is assumed as an essential condition.

Concluding Remarks

Our general theory involves more than one origin for the world's granitic melts. Small bodies have probably been formed by selective solution under conditions of regional (dynamic; also load?) metamorphism. Although several authorities believe that granite of even batholithic volume represents liquid residual from the single-course, non-repeated crystallization of basaltic or other basic magma, their conclusion is not proved. Repeated crystallizations and refusions of initially basic material does seem competent to have produced the granites of the primitive Sial (cosmic stage and early Archean of earth history). Locally the same process may have been at work in the case of some post-Archean granites. On the other hand, pure melting of old, anchi-cotectic granite should yield granitic liquid of later generation; and syntexis of Sialic rocks and basaltic liquid appears to be another cause for the formation of granite—secondary in this sense. Part of the evidence for both of these secondary modes of origin is to be found in a study of the diorite, granodiorite, syenite, and feldspathoidal clans.

[1] J. W. Judd, Quart. Jour. Geol. Soc. London, vol. 49, 1893, p. 545. G. W. Tyrrell, The Geology of Arran, Memoir Geol. Survey Scotland, 1928, pp. 234, 254.

CHAPTER XVIII

DIORITE CLAN

Rock Types. Chemical Character

Rosenbusch listed fifty species in the diorite family and the families of its dike and extrusive equivalents. "Diorite," like "andesite" and "porphyrite" is a "sack name," covering a variety of chemical and mineralogical types. For example, the diorites, so-called by authors, include quartz-free species and those containing modal quartz to the amount of 30 per cent. Similarly the range of chemical composition among the named species is wide. In fact some of the diorites and andesites are best classified otherwise and transferred to other clans. Nevertheless, the averages of the analyses of diorites and andesites fairly represent collective opinion as to the general nature of each major group.

These averages are stated in Table 52. The figures given in the second places of decimals and many of those in the first places have, of course, little significance. Table 53 gives the norms of the averages, computed as water free.

Table 52.—Average Plateau Basalt, Diorites, and Andesites
(Reduced to water free and to totals of 100)

	1	2	3	4	5	6	7	8	9
	43 plateau basalts	70 diorites (excluding quartz diorite)	55 quartz diorites	125 diorites (including quartz diorite)	All andesite (87 analyses)	33 augite andesites	20 hypersthene andesites	24 hornblende andesites	10 mica andesites
SiO_2	49.70	57.56	62.35	59.67	60.35	58.65	59.92	62.01	63.20
TiO_2	2.23	.85	.67	.77	.78	.80	.48	.43	1.67
Al_2O_3	14.24	16.90	16.41	16.68	17.54	17.67	17.51	17.91	16.35
Fe_2O_3	3.66	3.20	2.57	2.93	3.37	3.85	2.98	2.93	3.67
FeO	9.96	4.46	3.82	4.09	3.17	3.69	3.70	2.44	2.23
MnO	.17	.13	.10	.12	.18	.22	.15	.15	.21
MgO	6.82	4 23	2.83	3.62	2.78	2.90	3.31	2.48	2.06
CaO	9.55	6 83	5.45	6 22	5.87	5.92	6.66	5.88	4.11
Na_2O	2.64	3.44	3.41	3.50	3.63	3.60	3.44	3.88	3.61
K_2O	.70	2.15	2 13	2.13	2.07	2.40	1 65	1 74	2.48
P_2O_5	.33	.25	.26	.27	.26	.30	.20	.15	.41

TABLE 53.—NORMS OF AVERAGE PLATEAU BASALT, DIORITES, AND ANDESITES

	1	2	3	4	5	6	7	8	9
	43 plateau basalts	70 diorites (excluding quartz diorite)	55 quartz diorites	125 diorites (including quartz diorite)	All andesite (87 analyses)	33 augite andesites	20 hypersthene andesites	24 hornblende andesites	10 mica andesites
Quartz	.78	8.52	18.12	12 96	14 70	11.52	14 10	16 56	21 84
Orthoclase	3 89	12.79	12 23	12.23	12 23	14.46	10 01	10 01	15 01
Albite	22 53	29 34	28.82	29.34	30.92	30.39	28.82	33.01	30 39
Anorthite	25 02	24.74	23.35	23 91	25.30	25.02	27.52	26 13	17.79
Corundum	....	.....	....	...	.....	.....	....	. .	1.12
Diopside	17 03	6 02	1.58	4.26	1.76	2.01	3 80	1.76	
Hypersthene	20.55	12.76	10.16	10.90	8.15	8.88	10.17	7 08	5 10
Magnetite	5 34	3 56	3.71	4.18	4.87	5.57	4.41	4 18	3 03
Hematite	....	....	....	....	....	....	...	....	1.60
Ilmenite	4 26	1 67	1 37	1.52	1 52	1.52	91	.76	3 19
Apatite	62	62	62	62	62	.62	31	.31	93

Both tables illustrate a considerable chemical similarity ruling among the andesites and show the relationship of these to quartz diorite to be closer than to quartz-free diorite. The latter is really not an abundant type and seems never to form large bodies; every teacher of petrography knows the difficulty of securing adequate examples. On the other hand, quartz diorites are widespread, particularly within the limits of mountain chains and as phases of subjacent bodies, both stocks and batholiths. Though individually small, flows of andesite with little or no modal quartz have been accumulated in great total volumes along cordilleran belts.

Six modes of origin for rocks of the clan are conceivable: (1) the single-course differentiation of basaltic magma, (2) the separation of liquid formed during a certain stage in the remelting of crystallized basalt, (3) the syntexis of basalt and granite or other quartz-rich rock, with or without subsequent differentiation of the syntectic liquid, (4) the remelting and eruption of an earth shell of intermediate composition, (5) a combination of two or more of the processes (1) to (4) inclusive, (6) the eruption of primary dioritic or andesitic magma, undifferentiated and uncontaminated.

Thirty years ago the sixth hypothesis was favored by some petrographers, but, because of its failure to account for the actual field relations of the rocks of the clan and to accord with other fundamental facts, it is now generally rejected. None of the five other possibilities is opposed to the theory that fractionation of basic liquid has been

responsible for the more voluminous non-basaltic bodies of eruptive rock. Once more we note that remelting, including selective fusion, is in principle fractional crystallization in reverse, caused by appropriate rise of temperature.

Even with such speculative narrowing of the problem, a complete genetic account of the clan appears now impossible; too little is known about the structural and physicochemical relations. This chapter will attempt no more than a brief statement of the facts and deductions that bear on one or another of the first five hypotheses.

Andesites

Pyroxene Andesites.—Rosenbusch stated that he knew of no andesitic region without exposures of augite andesite. This effusive type may be charged with some phenocrysts of hypersthene and in fact is connected with hypersthene andesites by transitional varieties.

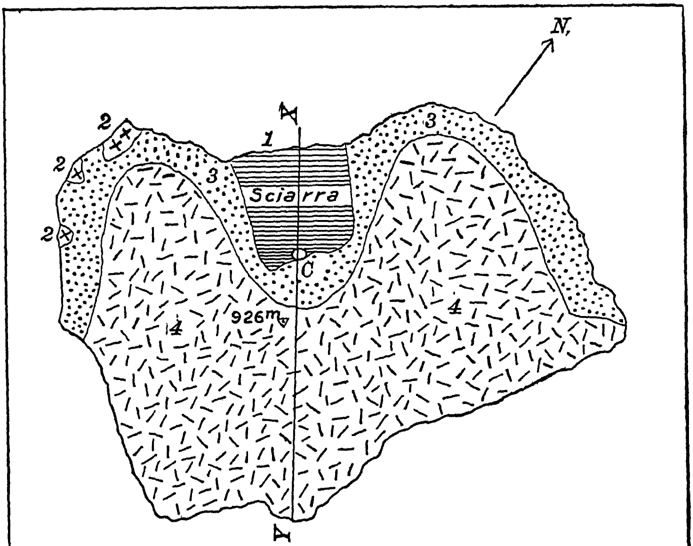


FIG. 154.—Map of Stromboli Island. *1*, youngest basalt; *2*, leucite basanite, where demonstrated; *3*, older basalt; *4*, andesitic lavas and tuffs of the original volcanic cone; *C*, crater. Scale, 1:68,000. (*After A. Bergeat, Abhand. k. bayer. Akad. Wiss., math.-phys. Kl., vol.* 20, 1899, *Tafel* 9.)

Columns 6 and 7 of Table 52 show the two species to be chemically almost identical; doubtless they have been developed under closely similar conditions.

Their intimate field association with flows of common basalt is well-known. Among the many examples from the lavas piled around central vents may be mentioned those of Stromboli (Fig. 154), Mull

Island, Fiji, and the North American Cordillera at the forty-ninth parallel of latitude.[1]

Pyroxene andesites are associated with the plateau basalts of the State of Washington (Figs. 155, 156), Wyoming-Idaho (Fig. 157), Skye, and the South African Karroo. It is possible, if not probable,

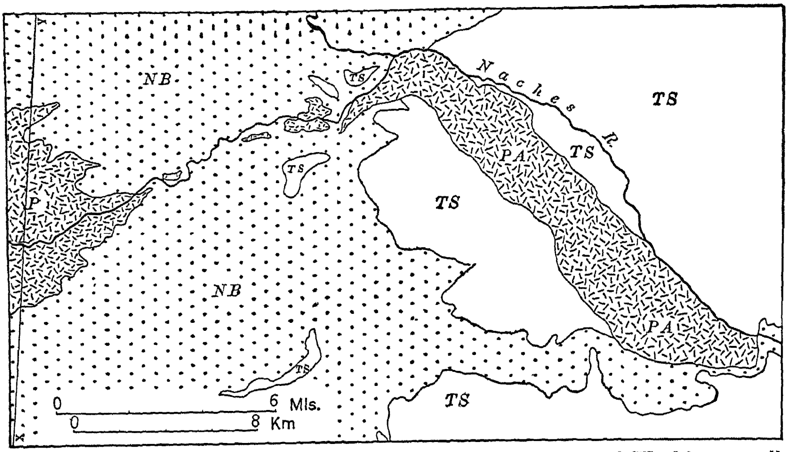


Fig. 155.—Map of part of the Ellensburg quadrangle, State of Washington, illustrating the close field connection between basalt and andesite. *TS*, Neocene and Pleistocene sands and silts; *NB*, Neocene basalt; *PA*, Pleistocene andesite. (*After Ellensburg folio, U. S. Geol. Survey*, 1903.)

that the andesitic lavas there issued from central vents that were temporarily active in these regions of dominant fissure eruption.[2]

The chemical and mineralogical relationship is no less evident, and one seems bound to assume the derivation of pyroxene andesite

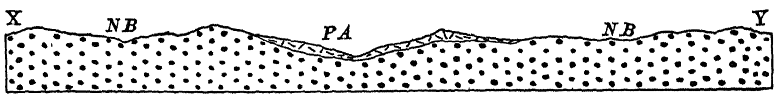


Fig. 156.—Section along the line *XY* in Fig. 155. Scale about 1:250,000.

from plateau basalt. In 1908 and 1914, the author offered the thesis that the mechanism involved is crystal fractionation.[3] Among the data used in those earlier statements were Streng's analyses of a porphyritic dolerite and its groundmass (columns 1 and 2, Table 54).[4]

[1] Mull memoir, Geol. Survey Scotland, 1924, Chaps. 23–25. W. G. Foye (Fiji), Proc. Amer. Acad. Arts and Sciences, vol. 54, 1918, p. 97. R. A. Daly, Mem. 38, Geol. Survey Canada, 1912, p. 782 and table of contents.

[2] A. Harker, Skye memoir, Geol. Survey Scotland, 1904, p. 38. A. L. du Toit, The Geology of South Africa, Edinburgh, 1926, p. 239.

[3] Jour. Geol., vol. 16, 1908, p. 401; Igneous Rocks and Their Origin, New York, 1914, p. 375.

[4] A. Streng, Neues Jahrb. f. Mineralogie, etc., 1888 (2), p. 211.

TABLE 54.—SOME CHEMICAL COMPARISONS
(Analyses reduced to water-free and to totals of 100)

	1	2	3	4	5
	Porphyritic dolerite (Streng)	Groundmass of dolerite of column 1 (Streng)	Average of 3 closely accordant analyses of Barren Island andesitic basalts (Washington)	Average of 6 analyses of Deccan plateau basalt, region near Barren Island (Holmes after Washington)	Average of 33 augite andesites
SiO_2	48 99	55.72	53.80	50 74	58.65
TiO_2	1 82	2.07	2.48	2.66	.80
Al_2O_3	13 41	15.53	17.97	13 23	17.67
Fe_2O_3	6.48	4.71	2.54	3 55	3.85
FeO	5.91	5.79	5.61	10 32	3.69
MnO	....	.....	.10	20	.22
MgO	9 56	4.24	3.38	5.81	2 90
CaO	8 90	7.70	9 76	10.30	5.92
Na_2O	3.42	3.49	3.44	2.32	3.60
K_2O	1.00	.75	69	.53	2 40
P_2O_5	51	. ..	23	.34	30

The analyses were made by the methods of forty years ago and are doubtless in some degree inaccurate; yet they suggest that the separation of the phenocrysts from the doleritic lava would have left a liquid rather closely akin to typical pyroxene andesite. In the same general way (by subtraction of early-formed crystals of olivine, magnetite, and ilmenite) we may reasonably explain the development of the andesitic basalt of Barren Island (column 3, Table 54) from the initially liquid Deccan plateau basalt (column 4).[1]

However, mere subtraction of crystals formed early during the crystallization of plateau basalt does not now appear competent to leave a liquid chemically identical with pyroxene andesite. For example, this process cannot easily account for the relative abundance of potash in the andesite (column 5). It looks as if this and some other oxides had been imported.

A relevant fact: sills or other injections illustrating the gravitative differentiation of basaltic magma (contaminated or not) rarely bear

[1] See the paper by H. S. Washington, Amer. Jour. Science, vol. 7, 1924, p. 452.

phases chemically identical with pyroxene andesite or its plutonic equivalent. Of these intrusions the more acid differentiates are usually quartz diabase, quartz gabbro, or granophyre-bearing rock. As far as the field evidence goes, then, pyroxene andesite has been seldom generated in closed chambers, while manifestly it has been generated in and below many volcanic pipes. Let us follow this clue and try to picture the changes in a vertical basaltic abyssolith.

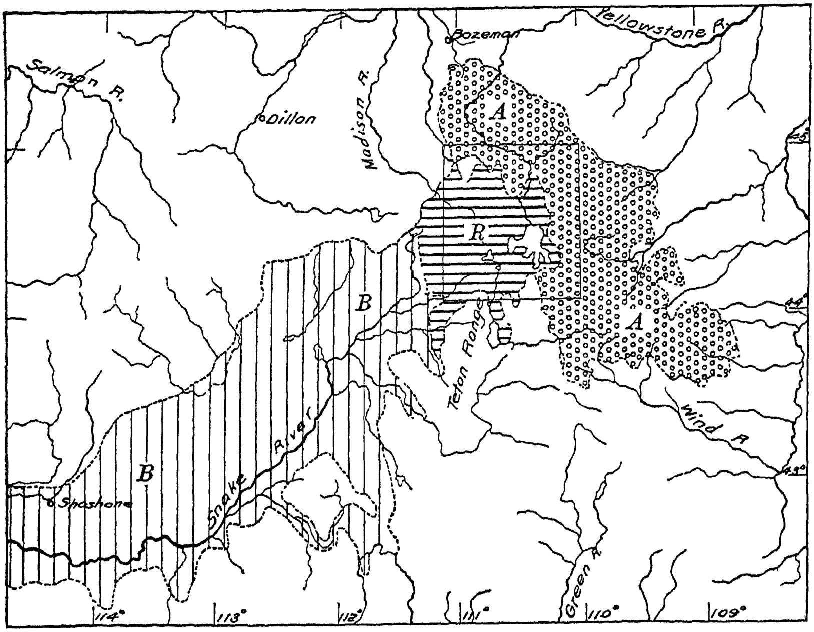


FIG. 157.—Map of Yellowstone Park (rectangle) and vicinity. *A*, andesitic pyroclastics and flows of Eocene and Miocene age (central eruptions); *R*, Pliocene rholite of the Park; *B*, Snake River basalt (fissure eruptions). Scale, 1:5,000,000. (*After J. P. Iddings, Quart. Jour. Geol. Soc. London, vol.* 52, 1896.)

The magmatic column, about 60 kilometers high, cannot behave exactly like the tiny melt of the laboratory. Because of its great depth the liquid is likely to be stirred by thermal convection, if not also by two-phase convection. Sinking of early-formed crystals, singly or in groups, is another reason for the cooling of the lower part of the magmatic column. Aided by pressure, crystallization is ultimately begun in the deep parts of the column. The comparatively light residual liquid at these levels rises and mixes with the liquid nearer the earth's surface. The risen liquid, arriving in a region of lower pressure, is somewhat superheated. Hence solidification of the upper part of the column is delayed, as it probably is also by gas fluxing (blowpiping and gas reactions).

For these reasons the magma of the upper part of the abyssolith becomes more salic by addition, as well as by the subtraction of early-formed crystals at the same levels. Gas fluxing, which prolongs the period of crystallization, tends to increase the quantity of the liquid developed by fractionation in place.

However, we must also allow for the possibility of deep-seated, selective fusion of Sialic xenoliths and wall rocks by the primary basaltic melt. Such incorporated material would necessarily rise and be mixed with any originating in crystal fractionation of the basalt itself.[1] The resulting layer of moderately salic liquid would be thick if the abyssolith is wide and narrows above into one or more volcanic pipes where the lighter liquids are concentrated and where the juvenile gases specially emanate. The great total quantity of andesite found at any individual center is therefore not an objection to the hypothesis.

The composition of the high-level liquid varies with the size and magmatic life of the abyssolith, with the amount of residual liquid risen from depth, and with the amount of selective fusion of rock, whether felsic or mafic.

That the Sial is thus involved in the generation of most andesites may be suspected also because of a fact of distribution. In spite of oft-repeated crystallizations of basaltic magma in the vents of deep-sea volcanoes, typical andesites are there absent or rare. None appears to have been reported from the intra-Pacific islands of Hawaii, Society group, Galapagos, San Felix-Ambrosio, the Paumotus; the open-ocean but probably peripheral islands of Samoa; the Atlantic islands of Saint Helena and Ascension; and the islands of Réunion, Mauritius, and Rodriguez in the deeper part of the Indian ocean.

In any case the addition-subtraction hypothesis accounts well for the large amount of normative quartz in average pyroxene andesite as well as in the three other main types of andesite.

Hornblende and Mica Andesites.—Varieties transitional between pyroxene andesite and each of the other andesitic species are common, and the average analyses of all do not differ greatly. Hence it is simplest to assume no very vital differences in the conditions of origin. The actual chemical and mineralogical contrasts represent a problem of unusual delicacy. The mechanism suggested for the pyroxene andesites seems flexible enough to permit an explanation of the other species in the same general way. How far concentration of water,

[1] That some syntexis of Sialic rocks goes on in the magmas from which andesitic rocks were derived is suggested by several reports of cordierite andesite (Osann, Molengraaff, and others), explained by the assimilation of foreign rock (*cf.* p. 408 and Rosenbusch's handbook, 4th edition, p. 1054).

resurgent or juvenile, has been important in the case of each of the two species is not clear. Perhaps the answer to these and associated questions may be found when sufficient information regarding the origin of the diorites is in hand.

Diorites

Rosenbusch considered the quartz-free diorites to be genetically connected with the alkali syenites, and the quartz diorites with the lime-alkali syenites, though holding also that diorite is in a continuous series with gabbro and granite. We have already glanced at the unsupported old speculation that intermediate magma, typified by the dioritic or andesitic, is wholly primary and the material from which the visible granites, basalts, and all other igneous types have been directly differentiated. Bowen recognizes two genetic series: (1) gabbro, diorite, quartz diorite, granodiorite, granite; and (2) gabbro, diorite, monzonite, syenite.[1] He explains diorites as a whole by the single-course crystallization of basaltic liquid. This hypothesis may apply to certain species, but for those more voluminous it encounters difficulties similar to those cited for the andesites. Like the chemical type corresponding to pyroxene andesite, typical quartz-free diorite seems never to have been found as a phase in any of the sheets and laccoliths that show evidence of gravitative differentiation in place (see Table 40). For some dioritic varieties, evidence of an origin in syntexis has been offered by various writers.

According to Gavelin and Högbom, small dioritic bodies in Sweden are of this origin, gabbro magma having dissolved granite in place. A dioritic facies of traplike feeders of the Cuddapah lava floods has been similarly interpreted. Miller explains certain Adirondack diorites as syntectics between gabbro magma and granite or gneiss. Tyrrell believes the "pure, homogeneous diorite and quartz-diorite" of Hybrid Hill and of Glen Dubh, Arran, to be "the final results of the complete solution of the gabbroidal rocks within the granite magma"; also that incorporation of feldspathic sandstone by basaltic magma in Arran has produced dioritic types of rock. Thomas finds an analogous origin for a diorite of Ardnamurchan.[2]

That many massifs of quartz-bearing diorite have batholithic or stock form and mode of intrusion seems as clear as in the case of the

[1] H. Rosenbusch, Mikroskopische Physiographie der massigen Gesteine, 4th ed., Stuttgart, 1907, pp. 275, 281, 286. N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 4.

[2] W. J. Miller, Jour. Geol., vol. 21, 1913, p. 177. G. W. Tyrrell, The Geology of Arran, Memoir Geol. Survey Scotland, 1928, pp. 172, 175–176, 191. H. H. Thomas, The Geology of Ardnamurchan etc., Memoir Geol. Survey Scotland, 1930, p. 155.

granites. Notable examples are found in Coast Range of Alaska and British Columbia; the Crazy Mountains, Montana; the Bradshaw Mountains and Globe area, Arizona; the Telluride area, Colorado; etc. For some of these bodies at least, the evidences of subjacent character and intrusion by replacement are as striking as those for granitic masses. In fact, diorites form peripheral phases of batholiths, otherwise and chiefly granitic. Thus at Garabal Hill (Scotland) augite, mica, and quartz-mica diorites appear along the contact of a granite massif. Delesse long ago found in the Vosges Mountains a case similar in principle. A third instance, in the State of Maine, is recalled by Fig. 113. The Scottish example, like those of Electric Peak, Klausen, and Peekskill (New York), illustrates the considerable chemical and mineralogical variability of individual bodies of diorite.

The bulkier diorites also may be of the hybrid origin described above. That they may be pure remelts of a deep sublayer of the Sial does not seem so probable. In the first place, the velocities of the earthquake waves at and just above the bottom of the Sial are apparently not high enough to warrant belief in a sufficiently thick sublayer of quartz diorite. And, second, large masses of quartz diorite seem to be rare in the interiors of the continents, while, as we shall see in the next chapter, they are abundant along circumoceanic cordilleras. This rule suggests a genetic condition associated not with the constitution of the normal Sial but with the world belt where the continental and suboceanic crust meet—a topic that merits attention when we come to the speculative treatment of the granodiorites of the circum-Pacific cordilleras. These, like the closely associated quartz diorites, will be hypothetically attributed to the special influence of the basic suboceanic crust on the composition of major hybrid bodies and their differentiates.

Summary

In accordance with the favored general theory, the species of the diorite clan are regarded as, in the final analysis, differentiates of a more basic liquid, the initial earth shell at the surface. Some andesitic basalts may represent the liquid residual from partly crystallized plateau basalt, this liquid being in place and not mixed with liquid of external origin. On the other hand, typical andesite seems to be more easily explained as a mixture of such residual liquid with the product of the selective fusion of foreign material, whether basaltic or Sialic. Drawing this tentative conclusion does not appear to be too bold a step, if the magmatic bodies whence andesites were derived had large volume. In fact, it is here assumed that these bodies are

characteristically abyssolithic, with a vertical dimension equal to the whole thickness of the earth's crust. In three-dimensional masses of the kind, vertical concentrations (additions and subtractions) are more likely to be important than they are in floored injections of normal moderate thickness, and *a fortiori* than they are in laboratory crucibles.

CHAPTER XIX

GRANODIORITE CLAN

Included Species

Opinions about the proper position of granodiorite and its close allies in rock classification differ considerably. We note three examples. Rosenbusch regarded granodiorite as a mere variety of quartz diorite and hence as part of the diorite family. Shand considers it to be a subdivision of the soda-granites. The author believes it should have the dignity of a distinct family, and Tyrrell agrees. The great volume of these rocks in the Cordilleras of North and South America alone is one reason for recognizing a distinct granodiorite clan.[1]

Table 55.—Average Analyses
(Reduced to water free and to totals of 100)

	1	2	3	4	5	6	7
	Average diorite	Average granite	Average "quartz monzonite"	Mean of 1 and 2	Average granodiorite	Average dacite	Average quartz diorite
Number of analyses averaged	70	546	20	.....	40	90	55
SiO_2........	57.56	70 77	67.41	64.17	65.69	66.68	62.35
TiO_2... .	85	.39	.51	.62	.57	.58	.67
Al_2O_3	16 90	14.59	15.76	15.74	16.11	16.50	16 41
Fe_2O_3	3.20	1.58	1.93	2.39	1.76	2 41	2 57
FeO.... ...	4 46	1.79	1.96	3.12	2.68	1.93	3.82
MnO	13	.12	.06	.13	.07	.06	.10
MgO	4.23	.89	1.43	2.56	1.93	1.44	2.83
CaO...... .	6.83	2.01	3.54	4.42	4.47	3.51	5.45
Na_2O........	3.44	3.52	3.45	3.48	3.74	4.03	3.41
K_2O.........	2 15	4 15	3.76	3.15	2 78	2.71	2.13
P_2O_5.........	.25	19	.19	.22	20	.15	.26

According to Tyrrell, the felsic and mafic limits of the granodiorite family are respectively adamellite and tonalite. The abundant

[1] S. J. Shand, Eruptive Rocks, London, 1927, p. 151. G. W. Tyrrell, The Principles of Petrology, London, 1926, p. 111. Compare Chapter 18 of the author's "Igneous Rocks and Their Origin," 1914.

so-called "quartz monzonites," intimately associated with the granodiorites, are partly granodiorites and for the rest granites with soda dominating potash. Few "quartz monzonites" have any evident genetic connection with monzonite itself.[1]

Table 55 shows the appropriateness of the name "granodiorite," a rock type which in average analysis so much resembles the mean between granite and diorite. The table also facilitates chemical comparison with dacite, quartz monzonite, and quartz diorite. Incidentally we observe how close quartz monzonite is, in average, to granite.

The clan includes the plutonic granodiorites, tonalites, some quartz monzonites, and some quartz diorites; the corresponding hypabyssal porphyries; and the effusive dacites with the quartz porphyrites.

General Field Relations

Like the granite massifs the larger bodies of granodiorite are classed as subjacent; they are crosscutting, without observable floors, and apparently replacing. The eruption of granodiorite was generally preceded by that of basaltic magma. In two outstanding ways its invasion of the crust differs from that by most granites. First, the interval between the eruptions of basalt and granodiorite was commonly marked by the large-scale eruption of quartz-dioritic liquid, which was much rarer or at any rate of smaller volumes in the basalt-granite sequence. Second, granodiorites tend to be followed by intrusive quartz monzonite, rather than by the more acid varieties of granite, which in so many regions followed the intrusion of normal granite. Both kinds of batholithic complexes are cut by dikes or other minor injections of basaltic liquid.

The most extensively exposed batholiths, those of the North American Cordillera, are of the composite class. The intrusions of each composite were commonly made in the following order: gabbro or its chemical equivalent, quartz diorite, granodiorite, quartz monzonite, soda-rich aplite. Throughout the 3000-kilometer belt, granodiorite seems to be dominant, though locally quartz diorite has a larger exposure. Many of the batholiths have central phases of granodiorite (with or without quartz monzonite) and contact phases or satellitic bodies of (mica, hornblende, or augite) quartz diorite. A number of the central granodiorites seem to merge gradually into the quartz diorite. Examples of these common types of association are described in the Sierra Nevadan Bidwell Bar, Big Trees, Colfax, Mother

[1] See Shand's (*op. cit.*, p. 177) excellent criticism of the misuse of the term "monzonite."

Lode, Redding, and Sonora folios of the United States Geological Survey; the Mount Stuart and Snoqualmie (State of Washington) folios of the same Survey; the Canadian Survey memoirs (Nos. 13, 26, 38, 158, etc.) dealing with the Coast Range of British Columbia; and reports on the Coast Range of Alaska. Buddington's map illustrates the widespread development of quartz diorite, granodiorite, and quartz monzonite in Southeastern Alaska.[1]

The contact phases of several of these batholiths are highly complex assemblages of gabbroic, dioritic, and quartz-dioritic rocks, apparently representing chilled phases of the batholithic magma as this became more and more salic at the upper levels of the respective chambers.

Similar associations of granodiorite with quartz diorite is characteristic of the Andean batholiths.

Dacite, which may be considered the effusive equivalent of granodiorite, has been found at many centers within the Cordilleras of the two Americas and is conspicuous among the lavas of the opposite Pacific border, from Bering Sea to Southern Australia. Though systematic petrography of that long stretch is still in the preliminary stage, it appears that these dacites are closely associated with lavas corresponding chemically with quartz diorite as well as with common basalt.

As Japan is being mapped, an increasing number of bodies of granodiorite and quartz diorite is described in that section of the circum-Pacific belt. For illustration see the texts accompanying the Okayama, Tajimi, Asuke, and Toyohashi sheets of the Imperial Geological Survey; also a number of memoirs published elsewhere and abstracted in the Japanese Journal of Geology and Geography.

Of course, bodies of rocks belonging to the granodiorite clan have been found in many other regions, but, as far as the earth has been mapped, it seems that these masses are comparatively small. So it is with the granodiorites described from the southern Appalachians, Massachusetts, Scotland, the Tyrol, the Riesengebirge, etc. Of recent years a considerable number of occurrences have been reported from the Pre-Cambrian complexes, especially the Canadian and Fennoscandian. However, not all of these last are true granodiorites. For example, while Mäkinen describes them as constituting about two-thirds of the post-Bothnian plutonics of a large area in central Fennoscandia, inspection of the potash-soda ratio shows these rocks to be better classed with the (somewhat basic) granites.[2]

Unlike granite, granodiorite has been seldom reported as a differentiate in sill or laccolith.

[1] A. F. Buddington, Jour. Geol., vol. 35, 1927, p. 226.

[2] E. Mäkinen, Bull. 47, Comm. Géol. Finlande, 1916, p. 142.

In the Port Orford quadrangle of Oregon, Diller mapped large gabbroic intrusions which seem to have laccolithic or chonolithic relations to the thick Cretaceous and older sediments of the region. The gabbro has dacitic phases. Diller interpreted certain dikes cutting the sediments as apophyses from the gabbroic masses. The dikes are composed of dacite porphyry and granodiorite. A similar association is found in connection with a big body of metagabbro in the adjacent Roseburg quadrangle.[1]

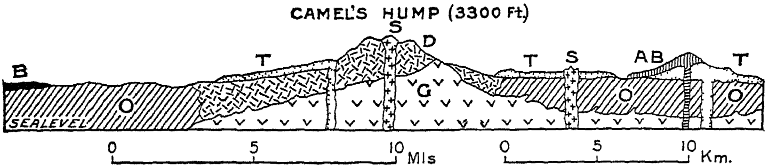


FIG. 158.—Section of Mount Macedon, Victoria, Australia, illustrating intimate association of dacite and granodiorite. *O*, Ordovician sediments, *G*, granodiorite; *D*, dacite; *S*, sölvsbergite; *T*, anorthoclase trachyte; *B*, normal basalt, *AB*, andesitic basalt. (*After E. W. Skeats and H. S. Summers, Bull.* 24, *Geol. Survey Victoria*, 1912.)

Figure 158 illustrates one of the many examples showing the syngenesis of granodiorite and dacite.

ORIGIN

Doubtless no one explanation applies to all the rock varieties of the clan. Yet voluminous and similarly related bodies of granodiorite outcrop in so many districts that this key type is likely to have been developed under a more or less uniform set of conditions. If these can be discerned, the genesis of much dacite also will be hinted.

Among the conceivable modes of origin of batholithic granodiorite may be listed (1) direct crystal fractionation of each of its bodies from primary basaltic magma, which existed as such when the corresponding petrogenetic cycle began, (2) pure melting of an assumed granodioritic sublayer of the earth's Sialic shell, (3) differentiation of mixtures of basaltic magma with secondary magmas, formed by selective fusion and assimilation of the varied rocks of the crust, including crystallized basalt.

1. Bowen is the leading advocate of the first hypothesis. While having some apparent justification in physicochemical theory, it is not satisfying, for reasons analogous to those already outlined in the case of batholithic granite. To repeat the statement of the difficulties seems hardly necessary.

2. The velocities of seismic waves in sublayer B of the Sial (Table 24, page 176) indicate the possibility that at least its lower part is

[1] J. S. Diller, Port Orford folio, U.S. Geol. Survey, 1903; Roseburg folio, *ibid.*, 1898.

chemically of granodioritic composition. Assuming this to be the case, we might further suppose the visible granodiorites of the world to be the erupted and crystallized products of pure remelting of primary granodioritic material from the lower part of the Sial. But the fusion, whether by subsidence into the hot substratum or by special radioactivity, would probably give not a granodioritic or dacitic liquid but a more salic liquid, gravitatively separated from the more refractory constituents of the imagined earth shell. Moreover, this hypothesis, like that of Bowen, does not account for the degree of concentration of the world's granodiorites around the Pacific Ocean.

3. The third speculation is more promising. A controlling fact is the common occurrence of granodiorite with batholithic relations in every way as typical as those so widely displayed by granite. Many granitic massifs have been interpreted as abyssolithic differentiates of syntectics. The syntectics are supposed to include products of pure melting of sunken Sial in the basaltic substratum and also products of true assimilation of Sialic rocks by substratum basalt, in place and after injection into the earth's crust. The separation of the big bodies of granite was possible because each major abyssolith was long liquid and because of the granitic character of much of the Sial. The granodioritic batholiths are fully as bulky as the granitic and presumably of as prolonged magmatic life. That the dominant high-level differentiate was finally no more salic than granodiorite seems, then, to suggest that the corresponding syntectics were somewhat less salic than those yielding granite.

This line of thought prompted the writing of the following passage, which appears in "Igneous Rocks and Their Origin" (pages 387, 389):

> Where sediments are batholithically replaced on a large scale, the chemical composition of both the batholithic syntectic and its more acid differentiate must be affected more or less strongly by the solution of the sediments or of the thick basaltic or andesitic beds so often laid down with the sediments. The suggestion is close at hand that rocks of the granodiorite clan are differentiates from syntectics containing considerable amounts of subsilicic sedimentary material.

The principal bodies of granodiorite discovered before 1914 were listed.

> These regions include nearly all the known volumes of granodioritic types and many of them contain the corresponding effusive, dacite. The relation of the dacite eruptions to country-rocks (so largely covered by the volcanics) is obviously often more obscure, but it is certain that most of the dacites described from the American Cordilleras have been erupted through relatively basic terranes. This is true, for example, for many localities in the northern Andes, where granodiorites do not crop out.

While the downstoping of supracrustal basic rocks can hardly fail to have some effect on the ultimate composition of visible abyssolithic rocks, this condition now appears quantitatively inadequate in the present problem. Perhaps more hopeful is a hypothesis based upon the new theory of some horizontal displacement of continents.

Granodiorites and dacites of great volumes are strung along the circum-Pacific cordilleras, the mountain chains that frame the deep Pacific basin, whether these chains be largely dry land or largely submerged. When the orogeny took place, the margins of the American, Asiatic, and Australian continents moved some distance toward the center of the basin. In Chapter XII we observed that such movement was probably made possible by successive downwarpings and founderings of the suboceanic crust in front of each continental block. Judged from the present isostatic condition of the crust, the part of it so displaced under the Cordilleran belt may be assumed to have been Sial-poor, if not Sial-free. If so, abyssal pure melting and assimilation under the belt could hardly fail to produce magmas less salic than those similarly formed beneath intracontinental chains of mountains. Since the thermal conditions were roughly similar, the dominant high-level differentiate of the circum-Pacific abyssoliths may well be granodioritic or quartz-dioritic and yet correspond to granitic differentiates of the intracontinental abyssoliths.

The special abundance of "quartz monzonite," soda-granite, and their allies in the circum-Pacific belt would find explanation, if these rocks truly represent late-formed liquids analogous to the younger, more acid granites of the intracontinental provinces.

Summary

This chapter emphasizes a question. Why, in most batholithic provinces, are the felsic differentiates typical granites, while in other provinces the dominating differentiates are more mafic and commonly granodiorites? Since the individual circum-Pacific bodies of granodiorite are at least as voluminous as the individual intracontinental bodies of granite, we cannot readily assume a systematic difference in the length of the magmatic lives, and therefore in the advance of differentiation by one kind of magma common to all batholithic provinces. The syntexis-differentiation hypothesis offers an answer to the question, on the assumption that the abyssal syntectics of the circum-Pacific belt differed chemically from the syntectics whence the typical granitic batholiths were derived. Why there should be this systematic difference is the chief speculative idea of the present chapter. On the other hand, bodies of granodiorite and its allies are not unexpected results of small-scale abyssolithic invasions of the Sial well inside the continental borders.

CHAPTER XX

SYENITE CLAN

The syenite clan includes the "subalkaline" and "alkaline" syenites (excluding the feldspathoidal syenites) and the monzonites, with their hypabyssal and effusive equivalents (trachytes, latites, etc.)—in all more than sixty named species. Appendix C of "Igneous Rocks and Their Origin" gives a rather full representative list of the localities where, in 1913, the species were known to outcrop. The members of the clan occur, and are evidently syngenetic, with members of the feldspathoidal clans; hence some of the principles affecting the problem of the syenites and trachytes will be more fully discussed in the next chapter. It will, in fact, be seen that there is no sharp dividing line between the conditions supposed to control the formation of these two groups of alkali-rich rocks. In both cases the importance of resurgent volatiles and of desilication of more acid magmas will be emphasized. Although there is contrast of quality between the kinds of contaminating material in the two cases, the principle underlying discussion of the syenite clan will be further illustrated in connection with the feldspathoidal clans.

Association with the Gabbro Clan

This is vividly illustrated by the small trachytic bodies cutting up through the dominant basalts of many volcanoes—for example, the bulky cone of Ascension Island, of which only a small part projects above sea (Fig. 159). Similar assemblages of basalt and trachyte (rarely syenite) characterize the Auvergne, Mull, Iceland, Jan Mayen, Madeira, Cape Verde Islands, Sao Thomé, Peter I Island, San Felix-San Ambrosio, Utsuryoto Island (Sea of Japan), Kerguelen, Christmas Island, Mozambique, Madagascar, Nyassaland, etc.

Syenites and monzonites belong in the same petrogenetic cycles with adjacent gabbros, norites, diabases, or basic porphyrites.

Within a single body a syenite or monzonite may be transitional into gabbro, diabase, or anorthosite.[1] Monzonite is of composition between gabbro and syenite and not seldom falls in the sequence

[1] Examples are found in the quadrangle covered by the Telluride folio of the U.S. Geol. Survey; in the diabasic intrusions of the Shinumo and Globe districts of Arizona, to be recalled later; and in the anorthositic areas of Norway.

between the two, when all three are of one cycle. The monzonite of the La Plata quadrangle, Colorado, is visibly transitional into diorite. The olivine syenite of Cripple Creek merges into normal olivine gabbro as well as into pyroxene syenite and pyroxene granite.[1] The "Sunlight" intrusives of northwestern Wyoming are quartz syenite, syenite-diorite, and gabbro, all merging into one another.[2]

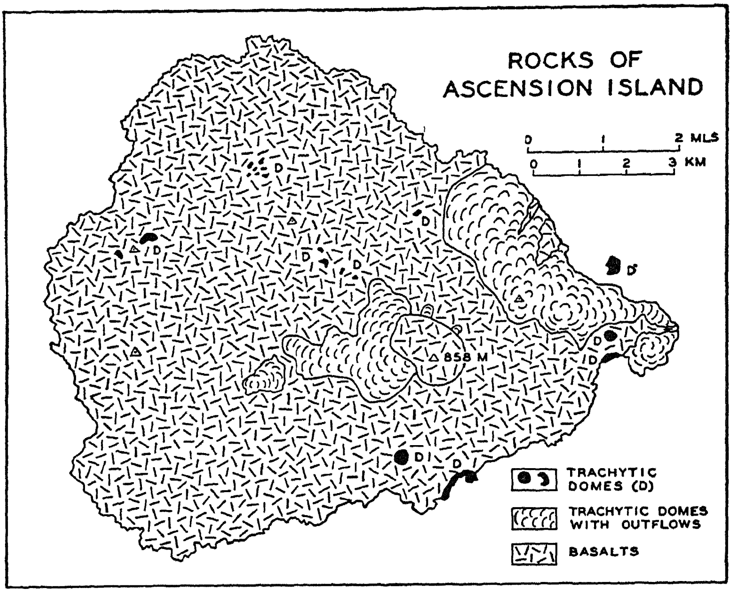


FIG. 159.—Trachyte plugs, crater domes, and stubby overflows in dominantly basaltic cone of Ascension Island. (*After R. A. Daly, Proc. Amer. Acad. Arts and Sciences, vol.* 60, 1925, *Plate* 1.)

Following the usual plutonic sequence, from basic to acid, a considerable number of syenitic intrusions have been respectively preceded by intrusions of gabbro or of essexite, a slightly modified gabbro. The diorite-gabbro body at Mount Ascutney, Vermont, is cut by nordmarkite-umptekite and pulaskite stocks. According to Adams, essexite is represented in all eight of the Monteregian Hills, Quebec (Fig. 160). At least six of them (perhaps all eight) have outcrops of syenite. The larger masses contain proportionately more syenite.[3] Among the many other examples are eruptives of Tripyramid (New Hampshire), the Adirondacks, north-central Wisconsin, southern British Columbia, Predazzo, Oslo region, and the Ekersund-Soggendal district (Norway).

[1] L. C. Graton, Prof. Paper, U.S. Geol. Survey, 1906, p. 55.
[2] Absaroka folio, U.S. Geol. Survey, 1899, p. 6.
[3] F. D. Adams, Jour. Geol., vol. 11, 1903, p. 251.

TABLE 56.—ANALYSES OF KIRUNA ROCKS

	1	2	3	4	5	6
	Diabase	Soda-greenstone	Syenite	Syenite porphyry	Whole syenitic body	Quartz porphyry
Number of analyses averaged	1	2	2	3	5	4
SiO_2	50 46	52.90	56 44	60.60	58 94	69.41
TiO_2	.60	1 37	1.81	1.22	1.45	38
Al_2O_3	20.08	14.20	14 67	16.21	15.59	13 92
Fe_2O_3	2 00	3 15	8 21	3.79	5.56	3.33
FeO	5.56	8 99	2 95	2.26	2.54	1.52
MnO	.10	.14	.21	.22	.22	.04
MgO	6 27	3 82	2.21	2.03	2.10	.64
CaO	10 33	7.31	3.90	3.91	3.90	.89
Na_2O	3 56	5 72	6.20	6 28	6.25	5.49
K_2O	68	.70	2.73	2 87	2 81	3.08
H_2O	.60	.96	.55	54	.56	.69
P_2O_5	12	.07	.22	19	.20	.05
S	.03	04	.01	.....	......	.02
CO_2	.....	64	....	.....	.....	.52
Total	100.39	100.01	100 11	100.12	100.12	99.98

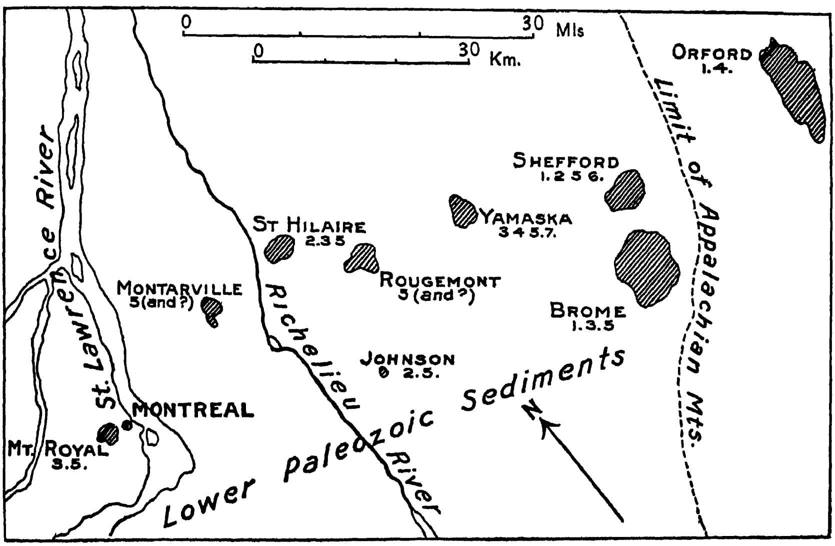


FIG. 160.—Map of Monteregian Hills, Quebec, showing rock occurring in each intrusive body. *1*, nordmarkite; *2*, pulaskite; *3*, nephelite syenite and laurvikitic syenite; *4*, monzonite and akerite; *5*, essexite; *6*, theralite; *7*, yamaskite (jacupirangite). (*After F. D. Adams*, *Jour. Geol.*, *vol.* 11, 1903, *p.* 241.)

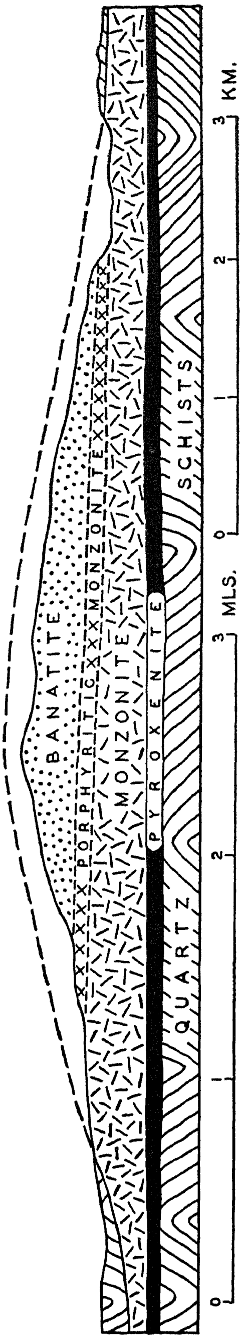


FIG. 161.—Section of the Mount Dromedary "laccolith."

A good illustration of the normal order of eruption is furnished by the Kiruna district, Sweden. The average analyses of Table 56, which have been compiled from the writings of Geijer and Lundbohm, are arranged in the time sequence, with the exception that columns 3, 4, and 5 refer to the same body.[1]

The extrusive species are not so obedient as the intrusive to the rule of a basic-to-acid sequence. Trachytes alternate with basalts and in some instances appear at the earth's surface before any basalt there becomes visible.

CHEMICAL CONTRAST OF PLUTONIC AND EFFUSIVE PHASES

The various members of the clan illustrate the usual kinds of chemical difference between the plutonic and volcanic phases of each magma. Columns 18, 19, 25, 26, 28 to 31 of Table 1 give average analyses of corresponding pairs. Here again we seem to find illustrated the tendency of magma to differentiate vertically, whether by direct gravity or by gaseous transfer, or by both methods.

SMALL SIZE OF BODIES

Every known body of trachyte or latite is of small volume. Neither type forms extensive fields of fissure eruption. Some masses of syenite have notable size and yet few are comparable to a first-class batholith of granite. In fairly typical illustration, the broad granitic Boulder batholith of Montana may be compared with the small (probably satellitic) bodies of syenite of the adjacent Elkhorn district.[2]

[1] Compare the association of quartz keratophyre and dolerite in New South Wales (W. N. Benson, Proc. Linn. Soc. New South Wales, vol. 40, 1915, p. 540), and in Pembrokeshire, Wales (A. H. Cox, Quart. Jour. Geol. Soc. London, vol. 71, 1916, p. 273).

[2] W. H. Weed and J. Barrell, 22d Ann. Rep. U.S. Geol. Survey, part 2, 1901, p. 518.

Differentiation in Place

A few syenites appear to be gravitative differentiates in floored bodies of dominantly gabbroic or diabasic (basaltic) magma. Noble studied a sill cutting the Unkar sediments at the Grand Canyon, Arizona. This sheet, 200 to 300 meters thick, is composed of olivine diabase overlain by hornblende syenite in "apparent transition." Other suggestive associations of syenite and diabase are exhibited in the Globe district of the same state.[1] Some intrusive sheets of Minnesota are charged with syenitic "red rock," specially developed at or near the upper contacts.

According to Brown, a more complex case, where the differentiating liquid was not basaltic, when emplaced, is represented at Mount Dromedary, New South Wales.[2] The "banatite" of the section (Fig. 161) may be regarded as a quartz-bearing syenite. Analyses of this and other phases of the laccolith are given in Table 57.

Table 57.—Analyses of Phases of the Mount Dromedary Laccolith

	1	2	3	4	5
	Banatite (syenite)	Porphyritic monzonite	Coarse monzonite	Shonkinite	Pyroxenite
SiO_2	64.49	59 44	51.09	48.34	43 63
TiO_2	.46	.54	1.02	.88	1.24
Al_2O_3	17.48	19.58	16.11	11.79	7 52
Fe_2O_3	1.64	.31	3.11	2 31	6 45
FeO	1.69	3.91	6.58	7.72	8.57
MnO	.11	.07	.18	.15	.20
MgO	.66	1.27	4.69	9.59	13.67
CaO	3.28	3.95	9.10	12 76	17.12
Na_2O	4.16	3.21	3.29	1.60	.36
K_2O	4.79	6.60	3.94	3.17	.50
H_2O+	.52	.88	.66	.68	.46
H_2O	.18	.12	.10	.04	.25
P_2O_5	.22	.07	.77	87	Trace
CO_2	.71	.49	Nil	Present	Nil
Total	100.39	100 44	100 64	99 90	99.97
Specific gravity	2.653	2 679	2.871	3 085	3.393

Hypotheses of Origin

Trachyte.—Study of some actual rock bodies and of petrographical literature published before 1914 led the author to the view that

[1] L. F. Noble, Amer. Jour. Science, vol. 29, 1910, p. 517. F. L. Ransome, Prof. Paper 12, U.S. Geol. Survey, 1903, p. 85.

[2] Ida A. Brown, Proc. Linn. Soc. New South Wales, vol. 55, part 5, 1930, p. 637.

trachyte is a derivative of common basaltic magma, either pure or contaminated. Its justice was made still more evident during the mapping of Tutuila, Ascension, and Saint Helena Islands (Figs. 162, 163).[1] No alternative mode of origin seems to match the facts of observation—including the close field association and the small volume of every known mass of trachyte.

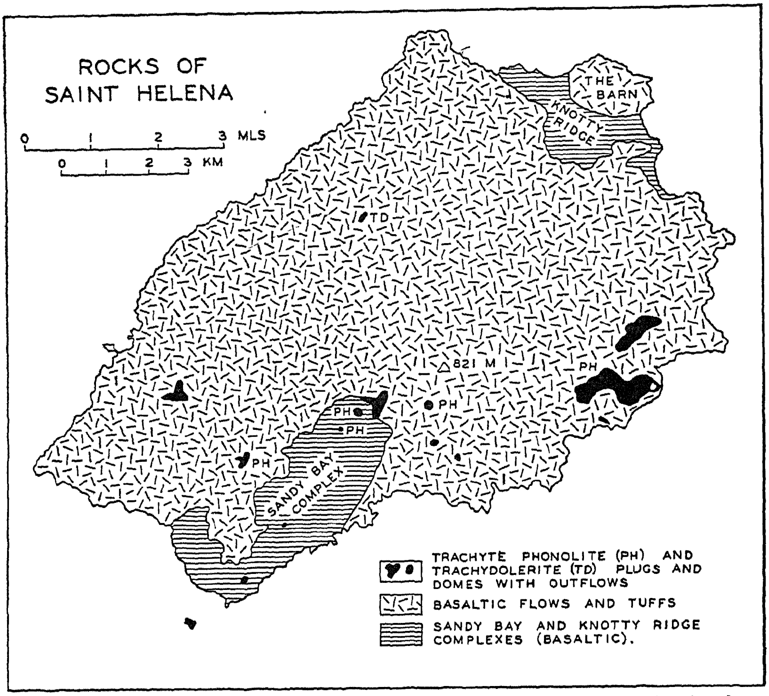


FIG. 162.—Plugs, domes, and stubby overflows of trachyte and trachytic phonolite in the dominantly basaltic cone of Saint Helena Island. (*After R. A. Daly, Proc. Amer. Acad. Arts and Sciences, vol.* 62, 1927, *Plate* 1.)

Less manifest is the mechanism by which the highly feldspathic lava has been differentiated. Yet certain facts narrow the field of speculative inquiry. (1) Trachyte characteristically fills narrow pipes, commonly subsidiary vents, run up through thick piles of the dominant basalts. Pipe fillings, endogenous (crater) domes, and flows of trachyte as well as phonolitic trachyte (Saint Helena) or a peculiar quartz trachyte (Ascension, Tutuila) constitute parts of the same, chiefly basaltic composite. (2) Many trachytes were generated late in the history of their respective volcanoes, as if the feeding abyssal injection had already lost some temperature. (3) The dis-

[1] I. Friedlaender (Zeit f. Vulkanologie, vol 9, 1926, p. 208) shares this idea in relation to the trachytes of the deep-sea islands.

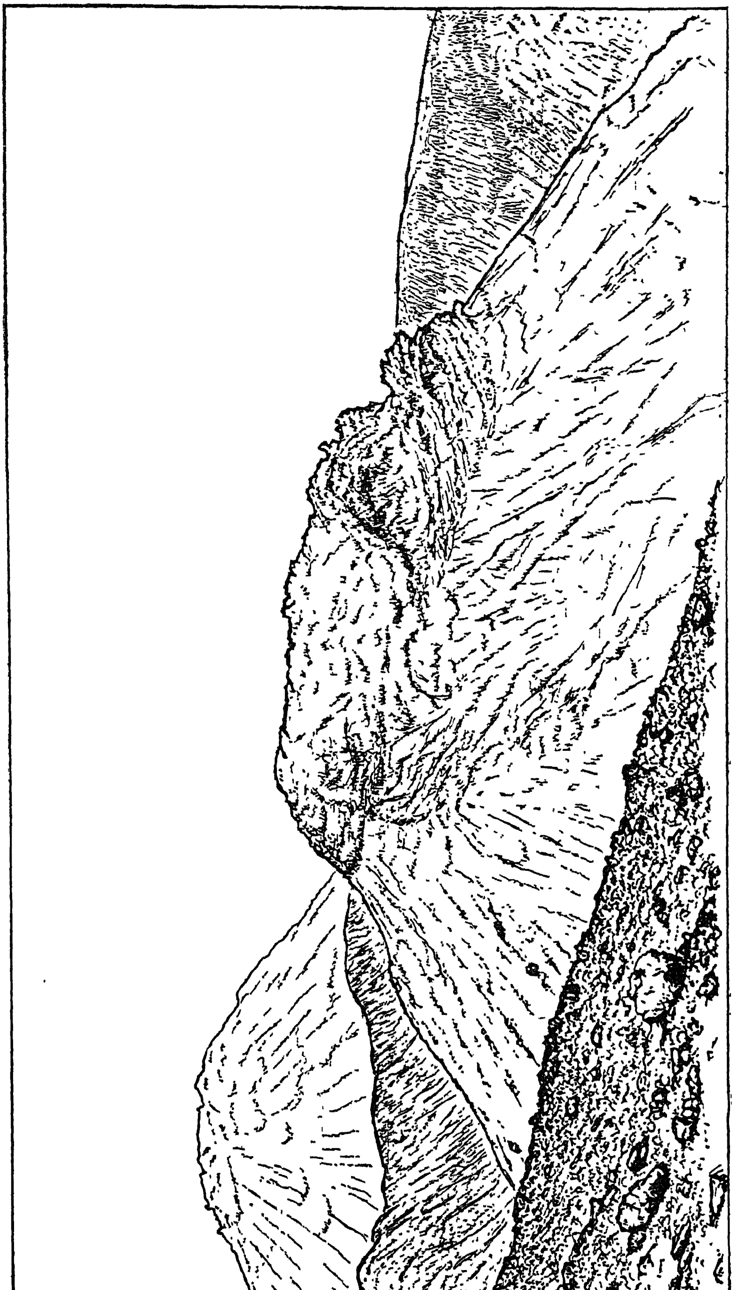


FIG. 163.—Little White Hill endogenous dome of trachyte, standing in a nearly circular crater rim of basaltic material (mid-ground and foreground), Ascension Island. White Hill trachytic dome in the background. Traced from a photograph. (*After R. A. Daly, Proc. Amer. Acad. Arts and Sciences, vol.* 60, 1925, *Plate* 7.)

covery of trachytic obsidians indicates a liquid state for this material when first formed. (4) Trachyte is notably free from, or poor in, bubble vesicles of the ordinary type, so common in andesitic and basaltic lavas. (5) Many effusions of trachytic magma have been immediately preceded by more or less violent explosions.[1] (6) Some of the composite cones bear trachyandesite, which seems to be one of the transitional liquids on the way from basalt to trachyte. Table 58 illustrates the case at Ascension and Tutuila Islands and shows a parallel relation among the world averages for plateau basalt, trachyandesite, and "alkaline" trachyte.[2]

TABLE 58.—AVERAGE ANALYSES OF BASALTS, TRACHYANDESITES, AND TRACHYTES
(Calculated as water free and to totals of 100)

	1	2	3	4	5	6	7	8	9
SiO_2	49 68	58 00	66.31	48.44	57 08	66 81	49 70	58 60	63.09
TiO_2	2 76	3 38	.43	4 29	2 29	.65	2.23	1 12	62
Al_2O_3	16 13	14 92	15.54	13.29	16.70	17.10	14.24	17 47	17.18
Fe_2O_3	4.02	1 73	3.49	4.06	3 26	2.13	3.66	4 02	3 03
FeO	7.47	5.78	1.13	8.27	4.69	1.34	9.96	3.22	2.00
MnO	.24	.11	.22	.15	.07	.05	.17	.05	.13
MgO	5.33	2.23	.27	8.21	2 38	.29	6.82	1 26	.63
CaO	8 78	4.50	1.08	7.72	4.43	1.63	9.55	4.26	1.52
Na_2O	3.70	5.88	6.42	3 47	6 31	5 40	2.64	5.75	6.30
K_2O	1.31	2.76	5 02	1.55	2.07	4 50	70	3.67	5.41
P_2O_5	58	.71	09	57	.72	10	.33	.58	.09

1. Average of 3 analyses of Ascension Island basalts.
2. Trachyandesite of Ascension Island.
3. Average of 5 analyses of Ascension Island trachytes.
4. Average of 5 Tutuila Island basalts.
5. Trachyandesite of Tutuila Island.
6. Average of 2 analyses of Tutuila Island trachytes.
7. Average of 43 analyses of plateau basalt (world).
8. Average of 12 analyses of trachyandesite (world).
9. Average of 19 analyses of "alkaline" trachytes (world).

Under the alternative name "oligoclase andesite," trachyandesite has been shown to be abundant among the younger lavas of Mount

[1] See the writer's memoirs on Ascension and Tutuila Islands (Proc. Amer. Acad. Arts and Sciences, vol. 60, 1925, p. 48; Pub. 340, Carnegie Inst. of Washington, 1924, p. 115); also H. H. Thomas, Mull memoir, Geol. Survey Scotland, 1924, pp. 185*ff*.

[2] I. Friedlaender (Zeit. f. Vulkanologie, vol. 9, 1926, p. 208) agrees that non-basaltic rocks of deep-sea islands are differentiates of basaltic liquid but offers no explanation of the chemistry of the derived species.

Perhaps significant is the lack of a chemical equivalent of trachyandesite in known differentiated sills; does this fact tend to corroborate the view that trachyandesite, like trachyte itself, has been formed with the aid of streaming gas, such as that normal to a volcanic pipe?

Etna, the basaltic lavas of the region being largely "pre-Etna."[1] The "latites" of San Francisco Mountain, Arizona, and some other regions seem to be rather typical trachyandesites, and there too syngenesis with common basalt is a natural supposition.[2] The same may be said of Cross's trachyandesite of Haleakala, Hawaii, and of Lawson's carmeloite.[3] The analogous mugearite of the Scottish Isles grades into oligoclase trachyte on the one hand and into basalt on the other.[4]

According to Bowen, trachytic magma may, under certain conditions, be produced by the pure crystal fractionation of basaltic liquid. From the analogies of artificial "dry" melts he notes two possibilities. First, sufficiently slow cooling of a basaltic magma may "permit the complete resolution of olivine (or of excess olivine)" and thus "determine a trachytic differentiate."

Again very rapid cooling, such that the liquid was cooled through the temperature range in which excess olivine separates, might permit a like result. The alternative involving slow cooling requires the additional assumption that some sort of stirring effect prevented segregation of the olivine, a possibility which can not be denied and may have been operative in some cases. But this combination of conditions does not seem as likely on general grounds as the rapid cooling of a rather small mass in its early stages, followed by a sufficient slowing-up of the cooling at later stages to permit some fractionation. The relative volumes of the rock types concerned are in accord with this general expectation. The trachytic differentiates of the Hebridean rocks are of insignificant volume and are therefore preferably to be referred to the differentiation of rather small masses of basaltic magma. The granophyric differentiates, on the other hand, occur in some volume and their content of free silica is to be referred to the separation of excess olivine from more considerable bodies of basaltic magmas at early stages, and failure of the resorption of olivine because of armoring or segregation to form bodies of peridotite, allivalite, etc. It is to be noted that, even in a very large mass whose liquid course was dominantly towards granitic composition, some part of the mass might have just the right amount of olivine to give barely complete resorption. The course of the liquid might thus locally be directed towards a trachytic differentiate.[5]

[1] H. S. Washington, M. Aurousseau, and M. G. Keyes, Amer. Jour. Science, vol. 12, 1926, pp. 388, 394, 407.

[2] H. H. Robinson, Prof. Paper 76. U.S. Geol. Survey, 1913, p. 136.

[3] W. Cross, Prof. Paper 88, U.S. Geol. Survey, 1915, p. 66. A. C. Lawson, Bull. Dep. Geol. Univ. California, vol. 1, 1893, pp. 38, 42.

[4] H. H. Thomas, Mull memoir, Geol. Survey Scotland, 1924, p. 143. W. Q. Kennedy (Summ. Prog. Geol. Survey Great Britain for 1930, part 2, 1931, p. 70) believes the syenite of the Hebridean province to have been differentiated from olivine-basalt liquid, with mugearite representing an intermediate step.

[5] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 238.

Although Bowen regards granitic or rhyolitic liquid as the commonest and most abundant rest magma from the crystal fractionation of basalt, he is well aware of the fact that rhyolites are unknown over vast areas of the ocean basins, where, however, many bodies of trachytes are found. He explains the contrast as follows:

> If our general thesis is correct the trachyte may be regarded as a derivative of the basaltic magma, differentiation having occurred through fractional crystallization of quite small bodies. The general tendency towards a trachytic differentiate might then be referred to a similar tendency towards small dimensions of the individual bodies of basaltic magma. The mechanics of the suboceanic crust are presumably at all times analogous to those of continents (especially their margins), during times of continental fragmentation. Intrusive activity finds its expression almost exclusively as dikes with occasional, relatively insignificant, plug-like expansions. There is never that tendency towards the formation of great cake-like masses of magma which is characteristic of continental mechanics. And there is consequently little tendency to form those differentiates of basaltic magma which result from slow cooling of the basaltic magma even in the very early stages of cooling. The dominance of trachytic material among the salic differentiates and the general lack of rhyolitic material would thus appear to be connected with the mechanics of the suboceanic crust.[1]

But it is by no means certain that the basaltic injections into the suboceanic crust have been small in either the absolute or relative sense. The tremendous piles of lava constituting a Mauna Loa, a Savaii, a Tahiti, or a Saint Helena imply a corresponding number of wide, deep, and therefore long-lived injections of basaltic liquid. Narrow dike feeders must freeze solid quickly and no one point along any of them could continue to supply flows for the hundreds of thousands of years during which these colossi of the central type were built. In any case the conditions determining whether trachyte or rhyolite would be differentiated, according to Bowen's general hypothesis, are admittedly somewhat delicate; and without further evidence one may well doubt his explanation of the absence of rhyolite in so many deep-sea islands. Again we may ask if a bulky rhyolitic liquid is ever the final rest magma from olivine basalt which undergoes a single course of crystallization.[2]

[1] N. L. Bowen, *ibid.*, p. 240.

[2] A. Holmes (Geol. Mag., vol. 68, 1931, p. 242) considers that at central complexes of the Mull and Ardnamurchan type, "the circumstances are not appropriate to the production of acid magma by differentiation . . . on the contrary, the differentiation processes there involved tend towards the generation of residual magmas of trachytic or syenitic composition."

Tyrrell accepts the crystal-fractionation theory for the trachyte of Jan Mayen but assumes that the parent basaltic magma was poor in water. The differentiation is supposed to have proceeded under low pressure, permitting the juvenile water to escape. Hence there was a "minimising or inhibition of the breakdown of the polysilicate molecules to quartz and biotite, and the precipitation of the $KAlSi_3O_8$ molecule as orthoclase at an earlier stage of crystallization than in the normal, 'wetter' mode of differentiation."[1]

In formal agreement is the remarkable freedom of trachyte from vesicles of the bubble type—a fact, however, which seems capable of a different interpretation, soon to be noted.

The Niggli-Tyrrell hypothesis is confronted with the fact that powerful explosions have immediately preceded the extrusion of many trachytes, showing the presence of much gas at the head of each magmatic column. The boring of the trachyte-filled pipes can hardly be explained except by assuming the emanation of hot gas rising with and through the pipe magma. Further, there is no apparent reason why oceanic volcanoes are so "dry" as to develop a trachytic end product of differentiation and rarely, if ever, be "wet" enough to furnish quartz-bearing lavas like those found on continents, continental islands, and submerged parts of the Sial.

In fact, the initial explosiveness and the evidence of gas fluxing seem to indicate the continued upward streaming of water and other gases at the vents where trachytic material was ultimately formed. The emanating gas may have favored the ultimate formation of a late trachytic liquid in several ways. (1) During the fluxing of the pipe through the older basaltic rocks, the alkaline constituents of these would first be liquefied or dissolved. Because of its low density such a secondary melt would tend to rise in the enlarging vent, and from this solution a late liquid, rich in the feldspathic molecules, might well be differentiated. (2) Preceding the initial explosions at trachytic vents, as just noted, great amounts of volatile matter were trapped within the magmatic column. The consequent lowering of viscosity could hardly fail to advance the differentiation of the parent basaltic liquid toward the extreme represented by trachyte. (3) If the rise of gas in special abundance were coupled with two-phase convection, the initially femic magma would be stirred, with a possible effect of the kind described by Bowen on the assumption that the basaltic

[1] G. W. Tyrrell, Trans. Roy. Soc. Edinburgh, vol. 54, 1926, p. 764. By the escape of water P. Niggli (Geol. Rundschau, vol. 3, 1912, p. 479) explains the absence of biotite and free quartz in the effusive rocks of the Electric Peak-Sepulchre Mountain complex of Montana, while these minerals are components of the corresponding plutonics. *Cf.* N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 84.

column cooled slowly (see above). (4) The gases, if rising in the free state, may be expected to transfer upward and concentrate the alkalies and other constituents of trachyte. Such action would be analogous to the feldspathization so often produced in solid country rocks by intrusive magma.[1] In this connection an experiment by Wells may be significant. He found that when potash feldspar is digested with water, in the presence of lime and at the pressure of 10 to 15 atmospheres, most of the potash goes into solution.[2]

Since solid trachyte is characteristically free or nearly free from bubble vesicles, any form of the present hypothesis demands that most of the fluxing gas escaped from the volcanic pipes before or during the crystallization of the trachyte.

Andesitic liquids are differentiated from basalt at pipes of similar dimensions, shapes, and structural relations. Here too the magmatic development has doubtless been aided by juvenile gas. The higher trachytic concentration of the feldspar molecules, especially potash molecules, seems to call for some different condition. Largely for this reason the author has stressed the hypothesis that water absorbed by basaltic magma from invaded shales and other hydrous rocks has controlled the formation of trachyte and phonolitic trachyte.

If analogy is to be trusted, we should ponder facts recorded by Walker.[3] The lower sill of Eilean Mhuire, one of the Shiant Isles, has a visible thickness of 60 meters, much of it being below water. The sill shows the following phases, named in order from roof to floor: (*a*) analcite dolerite, (*b*) teschenite, richer in analcite which here also is primary, (*c*) analcite syenite with acid segregations of syenitic

[1] A. Holmes and H. F. Harwood (Miner. Mag., vol. 22, 1929, p. 49) assume such gaseous transfer in the case of the "trachybasalt-trachyte association of rocks" in oceanic volcanoes. They express sympathy with the idea of selective fusion in depth as a process important in originating various rock types (see also their paper, *ibid.*, vol. 21, 1928, p. 538).

E. Lehmann (Zeit. f. Vulkanologie, Erg. Bd. 4, 1924, p. 181) believes that trachytic, trachyandesitic, and phonolitic magmas of Nyassaland were derived from "trachydoleritic" (basaltic) magma, not because of crystal fractionation but because of concentration of volatile substances. V. M. Goldschmidt, followed by J. H. L. Vogt (Videns.-Skrifter, Kl. I, 1924, No. 15, p. 89), attributes the formation of "alkaline stems" in Norway to the absorption of foreign water, the anorthosite-charnockite series there cutting "dry" granite and gneiss.

S. J. Shand (Quart. Jour. Geol. Soc London, vol. 89, 1933, p. 11) also favors upward "gas-streaming" as an important condition for the generation of trachyte and phonolite from basaltic liquid.

[2] H. L. Wells, Amer. Jour. Science, vol. 43, 1917, p. 485. Compare analogous experiments by W. H. Ross (Jour. Indust. and Eng. Chem., vol. 9, 1917, p. 467) and by R. J. Nestell and E. Anderson (*ibid.*, p. 646).

[3] F. Walker, Quart. Jour. Geol. Soc. London, vol. 86, 1930, p. 361. See also p. 398.

character, (*d*) dolerite. The phases are mutually transitional. An analysis of one of the syenitic segregations is given in column 1, Table 59.

TABLE 59

	1	2	3
SiO_2	58.36	56 94	56.44
TiO_2	.48	1.47	1.16
Al_2O_3	15 82	16 89	15.54
Fe_2O_3	4 87	3.73	3 27
FeO	2 53	3.36	3.67
MnO	.27	.17	
MgO	.59	.41	1.73
CaO	1.99	3.11	4.16
Na_2O	7 47	8.06	5 81
K_2O	4 31	3 86	4.27
H_2O+	2 62	.03	2 06
H_2O-	.72	.70	.44
P_2O_5	.35	1 02	.83
Rest	.04	.....	.97
Total	100 42	99 75	100 35

1. Syenite (segregation) in sill of Shiant Isles
2. Trachytic phonolite of Little Stone Top, Saint Helena (Proc. Amer. Acad. Arts and Sciences, vol. 62, 1927, p. 68).
3. Analcite syenite of Howford Bridge sill.

From Walker's account there can be little doubt that the analcitic dolerite, syenite, and teschenite are differentiates of basaltic magma in place. Further, his description is full of remarks indicating relative abundance of volatiles, especially water, in this sill. Thus he notes vesicularity of the rocks (druses, spherical vesicles), much hydrothermal alteration of the sill rocks, primary analcite associated with other hydrous silicates, baking (dehydration) of the intruded shales, and pegmatites and other coarse-grained developments in the sill.[1] Writing (page 360) of the conditions at a sill in an adjacent island, Walker states:

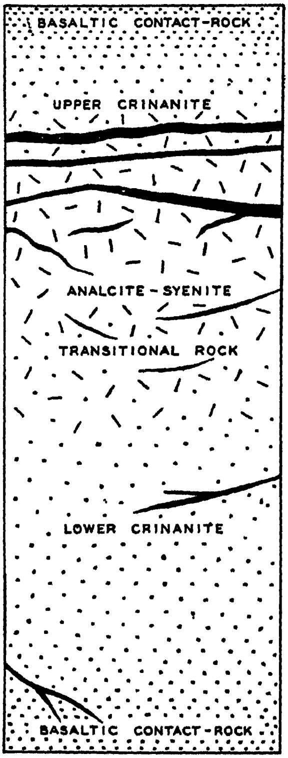
> The sediments appear to have floated up from the bottom of the sill, partly by ebullition of gas generated by reaction with the magma. Traces of this rush of gas-bubbles are now seen in the numerous spherical vesicles filled by radiating zeolites which occur in the igneous rock near the contact.

Similarly instructive is the Howford Bridge sill, Ayrshire. Though not over 33 meters thick, it was differentiated, yielding, between the

[1] The retention of water in the Utah sills described by J. Gilluly (Amer. Jour. Science, vol. 14, 1927, p. 203) explains the big (up to 7-centimeter) hornblendes of their analcite syenite, in spite of the thinness of the sills, none of which is more than 33 meters thick.

roof and floor chill phases, a layer of relatively basic analcite syenite which merges downward into crinanite (olivine-analcite dolerite). The syenitic layer is traversed by vein dikes of more felsic analcite syenite (Fig. 164). Tyrrell regards the case as one of "simple crystallization-differentiation" of an originally crinanitic liquid, a process controlled by gravity and by reactions between changing, residual, water-charged liquid and the successive crops of crystals. Column 3 of Table 59 gives the composition of the analcite syenite. Tyrrell does not discuss the origin of the water in the crinanite.[1] That it was absorbed from the series of Paleozoic sediments and tuffs underlying the district, as the basaltic magma made its way up, is one of the possibilities to be seriously considered.

ROOF



FLOOR

FIG. 164.—Vertical section of the 30-meter sill at Howford Bridge. (*After G. W. Tyrrell.*)

A somewhat parallel case, in the Kainei region of Korea, has been described by Ichimura. There laccoliths and dikes of trachydolerite are cut by narrow dikes and larger, pluglike intrusions of miarolitic analcite syenite containing essential orthoclase, augite, aegerite-augite, aegerite, and primary analcite. The feldspathoid as well as the miaroles prove some abundance of water in the younger magma. The character of the invaded sediments is not stated.[2]

A chemical comparison between either of the two syenites (columns 1 and 3 of Table 59) with a typical phonolitic trachyte (column 2) suggests that in the problem of the trachyte-basalt association the injected bodies may furnish more than a mere analogy. If gas control can be ultimately proved in the one set of conditions, it is reasonable to suspect gas control in the other.

Syenite.—The hypothesis concerning the effusive trachytes originated indirectly; it was a by-product of early studies of the

[1] G. W. Tyrrell, Quart. Jour. Geol. Soc. London, vol. 84, 1928, p. 559. The same writer (Trans. Geol. Soc. Glasgow, vol. 16, 1918, p. 352) states that "a connected series may be traced from olivine-dolerites devoid of alkali-felspar or analcite . . . to rocks which contain a notable amount of analcite or radial zeolites (crinanite)"; also that the ultramafic kylite is a common differentiate of crinanite and one complementary to the analcite syenite.

[2] T. Ichimura, Japanese Jour. Geol. and Geog., vol. 3, No. 3, 1924, p. 101.

plutonic syenites and was first published just after the author had completed the mapping of several, apparently subjacent bodies of syenite in British Columbia. These include the Coryell batholith, one of the largest masses of normal syenite yet described. The visible structural relations are in principle the same for all these British Columbia bodies, as for others studied in the field, including the syenites of Ascutney Mountain in Vermont, other New England syenites, and those of the Monteregian Hills (Figs. 160, 165). The habit of each body is that of a granitic stock or batholith. It seemed

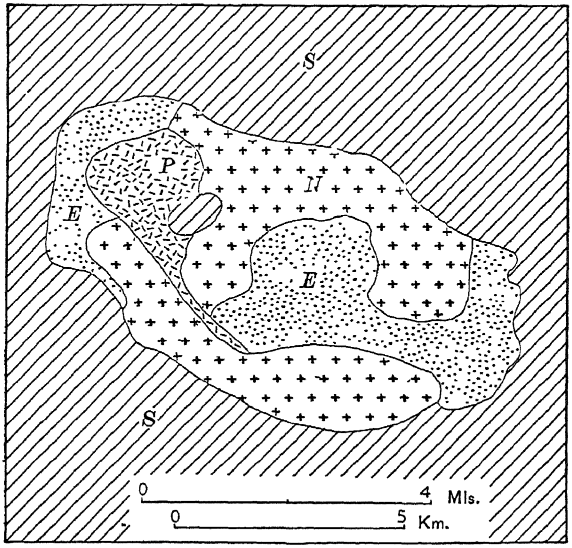


FIG. 165.—Map of Mount Shefford, Quebec. *S*, Paleozoic sediments; *E*, essexite; *P*, pulaskite, *N*, nordmarkite. (*After J. A. Dresser, Ann. Rep. Geol. Survey Canada, vol.* 13, *Part* L, 1902.)

highly improbable that the quartz-free or quartz-poor masses should have been derived from the same chemical kind of solution as that yielding the quartz-rich rock. A solution with a lower average content of silica is demanded. The logic of the situation thus led to the idea, phrased in "Igneous Rocks and Their Origin" as follows:

> Granting that the normal differentiate from the syntectic of basalt and the earth's acid shell is a granite bearing much free quartz, it follows that a syenite (like a granodiorite) is a differentiate from a syntectic of contrasted composition. That syntectic must be desilicated relatively to that from which a granite is produced. The only abundant crust rocks available for such a syntectic are basic sediments and, in a far less degree, basic igneous rocks. The theory seems, therefore, to demand that generally the members of the syenite clan shall show close field association with basic sediments or with basic igneous rocks, or with both classes of material. It is not essential

that these rocks shall crop out at the same level as the erupted differentiate; on the contrary, evidence should be sought that such country rocks were once in contact with the primary basaltic wedge *in depth* where their solution was possible.

Since a very large abyssal wedge, with average initial temperature, is likely to dissolve much of the earth's acid shell as well as the basic material with which it may contact, its syntectic magma will, in general, yield a granite or granodiorite by differentiation. The eclectic theory, therefore, implies that the abyssal wedge from which pure syenitic magma is differentiated is usually small. The rock bodies belonging to the syenite clan should be comparatively small in both area and volume.

For the syenites, magmatic syntexis with argillaceous rocks was particularly in mind, reactions with carbonate rocks being emphasized in the problem of the feldspathoidal families. Syntectics of the former kind should contain enough silica for the formation of orthoclase and albite molecules, and the salic differentiates should be free from, or poor in, feldspathoids. Shales, slates, phyllites, mica schists, and beds of basic volcanic origin have, in the continents, incomparably greater volume and also wider distribution than carbonate rocks and hence have had more opportunity to react with magmas. It is therefore significant that the total bulk of known syenitic bodies is much larger than the total bulk of the nephelitic and leucitic bodies in the plutonic class.

However, since such rocks as shales are doubtless of small importance under the deep oceans, the foregoing hypothesis does not well apply to the trachyte of the thalassic islands at least. Hence, while retaining the idea of the desilication of what might, without syntexis of the kind described, be normal granitic magma, a second suggestion was made: that volatiles, especially water resurgent from shales, tuffs, older lavas, and other hydrous rocks, have played a significant role in the formation of both syenitic and trachytic liquids.

TABLE 60.—PERCENTAGES OF VOLATILES BY WEIGHT

	Composite analysis of 253 sandstones	Composite analysis of 78 shales	Average for 18 phyllites	Average for 15 mica schists	Composite analysis of 345 limestones
H_2O	1.64*	5.02	...	...	.77*
CO_2	5.04	2.64	...	...	41.58
SO_3	.07	.65	...	...	.05
Cl	Trace	....	...	...	.02
Water or loss on ignition	.....	....	3.3	2.6	
Total	6.75	8.31	3.3	2.6	42.42

* Organic matter included.

From Clarke's composite analyses of sediments and from the averages computed from Rosenbusch's types of phyllite and mica schist, the relative abundance of volatile matter in these rocks may be appreciated (Table 60).[1]

Again we remember that resurgent gases from sediment, tuff, or schist lower the magmatic viscosity, lengthen the period of crystallization, and enable gravity to advance differentiation in the vertical sense.

Miller has suggested that the alternating shells of monzonite, syenite, hornblendite, and "biotite schist" developed at the contact of a gabbro stock in Warren County, New York, are due to the action of magmatic gases; were these partly resurgent?[2] Geijer explains the Näsberget magnetite body as a pneumatolytic excretion of diabasic magma. The diabase occurs in dikes paralleled by monzonitic and syenitic rocks into which the diabase merges. The syenites and ore are stated to be two phases of one pneumatolytic process of differentiation.[3] According to Heim, the kaersutite syenite of Karsuarsuk, Greenland, was formed under conditions largely pneumatolytic.[4] Brauns has offered a wealth of proof that the alkalies in combination with the volatiles were abundantly transferred upward in the magma chamber that furnished the Laacher See trachytic projectiles.[5]

Of 426 regions listed in Appendix C of "Igneous Rocks and Their Origin," 77 per cent show field relations which permit one to entertain the hypothesis of sedimentary control over the differentiation of syenitic and trachytic types, and in no case can the possible influence of resurgent water be definitely excluded.

Although 23 per cent of the listed regions give data which do not directly favor the hypothesis, it is of interest to note that certain syenitic bodies have been described as syntectic products by their respective students. According to Lacroix, granite magma in Madagascar absorbed mica schist, with the resulting formation of syenite bearing sillimanite and corundum; the adjacent schist was seen to be feldspathized. He states also that another Madagascar granite reacted with limestone in such a way as to produce a garnet-rich syenite containing primary calcite. Other syenitic hybrids described are

[1] F. W. Clarke, Bull. 491, U.S. Geol. Survey, 1911, p. 28. H. Rosenbusch, Elemente der Gesteinslehre, 3d ed., Stuttgart, 1910, pp. 561, 630.

[2] W. J. Miller, Science, vol. 36, 1912, p. 490.

[3] P. Geijer, Geol. Fören. Förh. Stockholm, vol. 33, 1911, p. 28.

[4] A. Heim, Medd. om Grönland, vol. 47, 1910, p. 219.

[5] R. Brauns, Neues Jahr. f. Miner, etc., B. B. 34, 1912, pp. 169–175; B. B. 35, 1912, pp. 211–218. S. Martius (Verh. Naturh. Ver. preuss. Rheinlande und Westfalens, Jahrg. 68, 1911, pp. 381–463) notes the excessive amount of gas in the Laacher See trachytic liquid.

monzonites, formed by the solution of gabbro in nephelite-syenite magma.[1] Sobral believes an old granite of the Nordingrå region of Sweden to have been melted by diabase magma, giving a monzonitic hybrid.[2] Kaiser concludes that both pulaskite and nordmarkite in Southwest Africa represent phases of an otherwise foyaitic (?) magma, where this had dissolved older granite along the contact.[3] According to Quensel, syenitic (?) rocks of southern Patagonia may have been derived from sedimentary syntectics; on the other hand, he thinks that part of the nordmarkitic rock at Almunge (Fig. 183) is probably due to syntexis between older granite and invading umptekitic magma.[4] More typically metasomatic is the syenitization of older granite of Norway by intruded alkaline magma.[5] Barrell postulated an assimilation of basic sediments by andesitic magma in the Elkhorn district, Montana, where syenite and quartz monzonite have been actually differentiated after andesitic eruption.[6] It is significant that the andesites are latitic. Miller credits the derivation of certain syenites of the Adirondack region from syntectics of gabbro magma with the Grenville gneiss-sediment series of rocks.[7]

Erdmannsdorffer explains the syenites of the Radau Valley, Harz region, as the product of selective fusion of orthophyric and tuffaceous rocks, heated by the large mass of the Harzburg gabbro magma. This, then, would be a case of palingenesis, without notable assimilation followed by differentiation, as suggested above for most post-Cambrian salic magmas. The selective fusion was *in situ* and was aided by the volatile substances emitted by the gabbroic mass. The process would furnish an analogy to the principle by which members of the diorite and granodiorite clans have been speculatively explained in their respective chapters, except that in these latter cases migration of the selective solutes is assumed.[8]

The importance of volatile matter in the generation of trachyte and syenite is a question fundamentally like that affecting the petrology of the feldspathoidal clans. Hence the fuller analysis of some main

[1] A. Lacroix, Minéralogie de Madagascar, Paris, vol. 2, 1922, pp. 457, 585, 626, 641.

[2] J. M. Sobral, Contributions to the Geology of the Nordingrå Region, Upsala, 1913, pp. 91, 124.

[3] E. Kaiser, Die Diamantenwüste Südwest-Afrikas, Berlin, 1926, vol. 1, p. 257.

[4] P. D. Quensel, Bull. Geol. Inst. Upsala, vol. 11, 1911, p. 112; vol. 12, 1914, p. 160.

[5] V. M. Goldschmidt, Econ. Geol., vol. 17, 1922, p. 105; Videns.-Skrifter, Oslo, Kl. I, 1920, No. 10, 1920, p. 135.

[6] J. Barrell, 22d Ann. Rep., U.S. Geol. Survey, part 2, 1901, p. 525.

[7] W. J. Miller, Jour. Geol., vol. 21, 1913, p. 178.

[8] O. H. Erdmannsdörffer, Abhand. Akad. Wiss. Heidelberg, math.-nat. Kl., Abh. 15, 1930, p. 58.

points in the next chapter has a direct bearing on the genetic problem of the syenite clan.

Conclusion

A single mode of origin for the rock species of the syenite clan is hardly probable, and a complete list of the actual modes may long elude formulation. Still more obscure is the quantitative importance of the various mechanisms.

The comparatively small volume of each rock body is explicable on the theory of origin through the crystal fractionation of basaltic liquid—and equally on the theory that each member of the clan is a differentiate from an appropriate syntectic, for this itself has necessarily limited volume. Since many syenites have structural relations essentially like those of typical batholithic granites, it seems reasonable to consider, here also, the possibility of abyssal pure melting and assimilation. The syenite-forming syntectics would in general, however, contain material won from mediosiliceous or basic shales, slates, or other hydrous rocks, including resurgent water. The dissolving liquids may be either the primary basaltic or those more acid, the latter themselves having resulted from differentiation or from the pure melting of Sialic rocks.

On the other hand, we have seen that many trachytic bodies appear to have been formed independently of the solution of basic sediments or other older rocks. These trachytes are commonly fillings of, or stubby outflows from, narrow pipes which had been fluxed up through basaltic piles around central vents. Here we can hardly doubt that the trachytic substance was derived essentially from the dominant basalt at each center. Two possibilities are indicated. The feldspathic material may have been separated from primary basaltic liquid, or in part at least prepared by the selective fusion of the pipe walls. The gases involved in the concentration or fluxing are assumed to be resurgent as well as juvenile. They are supposed to cooperate with crystal fractionation. Only a few varieties of rock belonging to the syenite clan are considered to be true hybrids, unaffected by differentiation.

CHAPTER XXI

FELDSPATHOIDAL CLANS

INCLUDED ROCK FAMILIES. DEFINITION

The expressions "alkaline magma" and "alkaline rock" continue to lack definition of universal acceptance. The need for it is readily illustrated.

In his systematic classification Winchell recognizes three major categories of eruptive rocks: alkaline, peralkaline, and alkalcic (alkali-calcic). The peralkaline group includes rocks carrying feldspathoids (nephelite, leucite, etc.). The alkaline group covers those with dominating alkaline feldspars as well as alkali-bearing pyroxene or amphibole and, among the felsic types, includes the quartz-bearing alkali-granites, alkali-granite porphyry, alkali-aplite, and alkali-rhyolite.[1]

Loewinson-Lessing defines "alkaline rocks" as those in which the total alkalies exceed the total of the alkaline earths. Hence he excludes essexite, melilite basalt, and analogous species. His definition takes in the majority of granites—not merely the so-called alkaline granites—along with many quartz porphyries, liparites, syenites, and trachytes.[2]

Shand has proposed a more restricted definition. His view may be given in his own words:

> In the commoner kinds of igneous rocks the alkali-metals are combined with alumina and silica in the molecular proportion of 1:1:6 (in felspars) or 1:3:6 (in micas). An alkaline rock, then, if names are to mean anything, should be one in which the alkalies are in excess of the 1:1:6 ratio, either alumina or silica or both being deficient. If silica is deficient, the alkalies and alumina form minerals that are unsaturated with regard to silica, such as the felspathoids, analcite and cancrinite, in which the molecular ratio is 1:1:(4 or less). If alumina is deficient, the deficiency may be made up by ferric oxide, zirconia or titania, giving such minerals as ægirine, riebeckite and eudialyte, in which the molecular ratio is again 1:1:(4 or less). The simplest way to define an alkaline rock, then, is to say that it contains minerals in which the molecular ratio of alkali to silica is not less than 1:4. A more technical definition would be as follows: An alkaline rock is one which contains normal metasilicates or orthosilicates of alkali-metals with aluminium, iron, zirconium or titanium, with or without other minerals.

[1] A. N. Winchell, Jour. Geol., vol. 21, 1913, p. 208.

[2] F. Loewinson-Lessing, Bull. soc. belge de géologie, etc., vol. 32, 1922, p. 56.

The difference between this definition and the current conception of an alkaline rock is that an excess of alkali-felspar (which is a polysilicate) or of mica (which is an acid silicate) does not in my view entitle a rock to be called alkaline. The advantage of the definition is that it cuts out that doubtful borderland where it becomes a matter of individual opinion whether a rock is to be considered alkaline or not; and that it leaves us with a clean-cut natural group in which every rock contains either an excess of alkali over alumina or an excess of alkali and alumina over the available silica.

Among the rocks so defined we can distinguish three groups:

I. Chemical character: Silica adequate or excessive, alumina deficient.
Phases developed: Felspars, ægirine, riebeckite, eudialyte, etc., with or without quartz.
Typical rocks: Ægirine granite, umptekites, comendites, etc.

II. Chemical character: Alumina adequate or excessive, silica deficient.
Phases developed: Felspathoids, micas, corundum, olivine, etc
Typical rocks: Mica-foyaites, corundum-foyaites, etc.

III. Chemical character: Both silica and alumina deficient.
Phases developed: Felspathoids, ægirine, riebeckite, barkevikite, olivine, etc
Typical rocks: Ægirine foyaites, tinguaites, etc.

This grouping expresses something more than just the hair-splitting tendencies of a systematist, for it shows at once, when we come to consider the vexed question of the origin of the alkaline rocks, that we ought not to expect to find a unique solution of the problem. A deficiency of silica in one end-product, and a deficiency of alumina in another, are not likely to result from one and the same reaction. No theory of the alkaline rocks can be complete unless it explains all three of the above cases, and not just one of them.[1]

Shand's definition is likely to appeal to petrographers of the future, and probably none will disagree with his statement that the origin of the alkaline group as a whole must be multiple The separate treatment of the alkali-rich granites, the syenite clan, and the feldspathoidal clans in as many chapters of this book and also of "Igneous Rocks and Their Origin" is sufficient evidence that the author regards a "unique solution of the problem" of the alkali-rich rocks as impossible. Since certain critics have failed to grasp the fact, some actually holding that the author explains all alkali-rich rocks by limestone-syntexis, it has seemed well to change the title of this chapter from "Alkaline Clans" to "Feldspathoidal Clans." Here rocks undersaturated with silica, so that feldspathoids have crystallized instead of or alongside of feldspars, are primarily discussed, and it should be noted at once that some feldspathoidal rocks can hardly be ascribed to magmatic reaction with limestone. Some basic types, not characterized by essential

[1] S. J. Shand, Proc. Geol. Soc. South Africa, vol. 25, 1922, p. *xix*. On p. *xxviii* Shand writes: "The problem of the alkaline rocks is a double problem, involving first a concentration of alkali-rich molecules, and second a process of desilication."

feldspathoid, demand attention, because their field relations plainly indicate common origin with their feldspathoidal associates.

Thus five of the ten plutonic families listed by Rosenbusch will be considered together. They are (1) the family of the nephelite syenites and leucite syenites, (2) the family of the essexites, (3) the family of the shonkinites and theralites, (4) the family of the missourites and fergusites, and (5) the family of the ijolites and bekinkinites. Adding dike and extrusive equivalents and differentiates, the total number of species involved is about two hundred or nearly one-third of all named species of igneous rocks.[1]

The expression "alkaline group or suite" will, then, be used not as a chemical description of every included species but rather symbolically, to emphasize, as Rosenbusch did, the syngenesis of the whole group, in which leading types are literally rich in alkalies; other types, like limburgite, nephelite basalt, melilite basalt, basanite, or tephrite, are not absolutely rich in soda or potash. On the other hand, the use of the somewhat metaphorical expression does not obscure the fact of a more indirect genetic association of feldspathoidal rocks and the abundant subalkaline species.

THEORIES OF ORIGIN

Published suggestions regarding the origin of the strongly alkaline, unsaturated magmas and their differentiates are of two kinds. According to the first group of hypotheses, those magmas are assumed to have formed one or more original bodies within the earth—primeval masses, developed during the "foundation of the world." Their differentiation after eruption to higher levels is supposed to have produced the many species of the "alkaline" suite. The second group of hypotheses agree in explaining these species as differentiates of subalkaline magma, either pure or else contaminated with foreign materials, such as sedimentary rocks and resurgent gases.

Derivation from Magmas Originally Rich in Alkalies

Some hypotheses of the first group are now of little more than historical interest. These include the *Kern* idea of Rosenbusch and also Becke's original conception of the Atlantic and Pacific suites of igneous rocks. Although his *Kern* hypothesis helped Rosenbusch, master petrographer, to his proof of the importance of alkaline types, the mechanism connecting *Kern* and rock remained vague in the extreme. For this and other reasons the idea is not acceptable to other petrographers. Becke's first view, that the feldspathoidal

[1] The long list of newer specific names may be compiled from the last edition of A. Holmes's highly appreciated "Petrographical Nomenclature."

types were derived from an alkali-rich, primeval earth shell (Atlantic magma) underlying a somewhat less dense, subalkaline earth shell (Pacific magma) is so little supported by geological or other facts that Becke himself has abandoned it.

A few authorities, studying comagmatic provinces, have assumed the existence of originally segregated bodies of alkali-rich magma within the earth, eruptions from these primitive masses being responsible for the alkaline provinces. In no case has any cause for such original heterogeneity of the globe been suggested. Among the grounds for doubting the validity of the idea are the following:

1. The total volume of the known feldspathoidal rocks is vanishingly small when compared with the total volume of rocks belonging to any one of the gabbro, granodiorite, or granite clans. The largest known body of feldspathoidal rock is much smaller than the largest known body of gabbro, norite, granodiorite, or granite. If the imagined primitive "alkaline pockets" remained liquid so as to be eruptible at intervals of Paleozoic, Mesozoic, and Cenozoic time, those "pockets" must have been huge; otherwise they would have frozen long ago. If so voluminous, some of their emanations should have occurred on a big scale; for alkali-rich magmas appear to have average viscosity at least as low as that characterizing the normal subalkaline magmas, and there is no reason to assume any systematic difference in the conditions of eruption. Hence the actual smallness of feldspathoidal bodies seems to defy explanation by the hypothesis.

2. Many a so-called alkaline province contains important masses of subalkaline eruptives belonging to the same petrogenetic cycle as the more strongly alkaline rocks of the province. Unfortunately this fact has been somewhat obscured by arbitrary classification. For instance some basic rocks in alkaline provinces have been almost automatically described as essexites, thus implying a source in alkaline magma, though these same rocks are really gabbros. Similarly basaltic rocks associated with phonolites have been called trachydolerites.

3. Transition of a feldspathoidal type into one relatively poor in alkalies and completely lacking in feldspathoids, and hence *per se* of subalkaline character, is sometimes observed.

4. Geophysical research has failed to find evidence of primitive, large-scale, horizontal heterogeneity of the earth, except that represented by the contrast of the dominantly granitic Sial with the Simatic crust under the deep oceans. Washington's argument for greater horizontal heterogeneity is based on regional averages of chemical analyses. Since these are doubtless not proportioned to the rock volumes, any definite detailed conclusion regarding the constitution

of the outer earth is not to be expected. In any case Washington himself does not regard horizontal heterogeneity within the limits of the continents as a feature dating from the planet's primary organization.[1]

5. Again, the speculation is not to be reconciled with the common alternation of alkali-rich and subalkaline eruptives in the same region. An example is seen in the contrasts of Ordovician (mixed character), Old Red Sandstone (subalkaline), Carboniferous (alkaline), and Tertiary (chiefly subalkaline) igneous rocks of Great Britain.[2] The big subalkaline eruptions of the mid-Mesozoic in British Columbia were succeeded by many strongly alkaline eruptives of the earlier Tertiary, and these by still younger subalkaline basalts. Indeed, few petrogenetic cycles have produced only strongly alkaline or feldspathoidal types.

Apparently, therefore, the alkaline and subalkaline suites are not independent, as regards either space relations or time relations. This fact underlies Bowen's statement that "field facts leave no possible doubt" that the two suites have been derived from the same kind of liquid or liquids.[3] Among others who agree are Daly, Evans, Harker, Holmes, Shand, Smyth, Tyrrell, and J. H. L. Vogt. Barring details of the actual mechanism, all these writers believe crystal fractionation to be one of the principal processes involved in the development of alkali-rich rocks.

Derivation from Uncontaminated Subalkaline Liquid

A considerable number of the specialists on the problem have concluded that the generating subalkaline magmas were not essentially affected by either the assimilation or the pure melting of foreign solid rock.

Bowen's Hypothesis.—With the possible exception of certain melilitic rocks, Bowen explains the feldspathoidal types and their syngenetic associates by the differentiation of pure basaltic liquid, notwithstanding his own view that, when this differentiation occurs on a big scale, it normally gives species free from feldspathoids. In successive publications he has discussed the problem "how rocks containing feldspathoids and rocks transitional towards these may be developed from magmas which ordinarily give rise only to quartzose late differentiates."

Bowen's answers to this question may be summarized partly in his words:

[1] H. S. Washington, Bull. Geol. Soc. America, vol. 33, 1922, p. 375.

[2] See A. Harker, Quart. Jour. Geol. Soc. London, vol. 73, 1918, p. *lxxxviii*.

[3] N. L. Bowen, Jour. Geol., vol. 23, Supp., 1915, p. 59.

The most prominent feldspathoidal rock is nephelite syenite and in a former publication a mode of origin of nephelite syenites was suggested in which the corresponding magma was regarded as the residual liquid of granitic magma, crystallized in the appropriate manner. Reliance was placed on the indications, furnished by the presence of biotite in granite, that, in the presence of water, there is a tendency towards the breakdown of the feldspars into the orthosilicate molecules of the micas, with setting free of SiO_2. . . . As a result of precipitation of the other molecules in the form of mica and quartz, there would be a concentration of the $NaAlSiO_4$ molecule in the residual liquor at a certain stage. The separation of the residual liquor, probably by a squeezing-out process, might then occur and thus an independent liquid might originate.[1]

In his book, later published, Bowen notes some of the difficulties with this older hypothesis but does not abandon it, while suggesting a quite different idea, founded upon the incongruent melting of orthoclase. His evidence comes from the behavior of certain artificial melts. He first attempts to show how the fractionation of basaltic magma leads to a trachytic residual liquid, rather than to the normal granitic residual. He attributes the former result to special conditions that cause the complete re-solution of the early-formed crystals of olivine. The re-solution is assumed to be due to "the rapid cooling of a rather small mass in its early stages, followed by a sufficient slowing-up of the cooling at later stages to permit some fractionation." By the removal of pyroxene a trachytic residual liquid is necessitated. In this liquid, under certain conditions, leucites are supposed to form. If by any means these crystals are segregated, the remaining liquid will be switched over "into an alkaline line of descent." It will "proceed ever towards the phonolitic eutectic."[2]

The delicacy of the assumed mechanism is apparent. Can one withhold assent from Shand's adverse criticism? He writes:

It will be observed that for the development of a foyaitic fraction from a basaltic magma Bowen's theory demands a remarkable conjunction of favourable circumstances. The liquid must twice be strained off from the early-formed crystals, and in each case this must happen at a crucial moment, after crystallization has proceeded far enough to produce the desired effect and before the temperature is reached at which reaction would set in and destroy the effect. If Bowen's postulates are all granted, it seems that a very small body of foyaite might originate in this way, say once in a million times; but to suggest that all nepheline rocks have been generated under such

[1] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, pp. 234–235. S. J. Shand (Proc. Geol. Soc. South Africa, vol. 25, 1922, p. *xxvii*) puts his finger on a logical objection to this earlier hypothesis of Bowen. It is indeed hard to reconcile it with the fact that "the residual liquor from granitic magma is invariably highly siliceous." *Cf.* R. A. Daly, Jour. Geol., vol. 26, 1918, p. 128.

[2] N. L. Bowen, *op. cit.*, pp. 238, 253.

remarkable conditions is to put a far, far greater strain on the probabilities than the most extreme supporter of the assimilation theory has ever done.

Shand goes on to show how weak is the field evidence adduced by Bowen in favor of his theory.[1]

The work of Thomas and his colleagues in the British Tertiary province furnished Bowen with some of the data on which his own general theory of rock origins is based, and Thomas accepts the theory with but few reservations. Yet it is a question whether Bowen's theory can be reconciled with Thomas's suggestion that the Mull

. . . Alkaline Series owes its origin to the more or less complete crystallization of the [parental] plateau basalt magma, without the interim withdrawal of solid phases . . . accompanied by a strong concentration of the volatile constituents . . .

the alkaline magma thus "representing the normal alkaline mesostasis of such basic rocks as are formed by the more or less rapid cooling of the undifferentiated plateau magma."[2]

Harker's Hypothesis.—Differentiation of magmas by the winepress mechanism has been applied by Harker specially to the alkaline rocks.

Conceive an extensive tract to be underlain by a zone which is neither solid nor liquid, but composed of crystals with an interstitial fluid magma. If this be subjected to different pressures in different parts of its horizontal extent, its uniformity will necessarily be disturbed, the fluid [normally the more alkaline] portion being squeezed out at places of higher pressure and driven to places of lower pressure.

And again:

If at any stage of progressive crystallization, or progressive fusion, a separation or partial separation is brought about between the fluid and the crystalline part, the former will be relatively rich in alkali, and particularly in soda, while the latter reciprocally will be rich in lime and magnesia. As regards the mechanism of such separation, Bowen lays stress especially upon the sinking of crystals in a mass which is still mainly liquid. Simple physical considerations, however, tell us that a great liquid or mainly liquid reservoir within the earth's crust can have only a temporary status. It is doubtless incidental to the existence of much more extensive tracts of the lower crust in a semi-liquid state, that is, as a liquid crowded with crystals or a crystalline fabric with interstitial liquid. Such a condition must be postulated beneath any region which is the theatre of long-continued igneous activity, and a mass

[1] S. J. Shand, Geol. Mag., vol. 67, 1930, p. 425.

[2] H. H. Thomas, The Geology of Ardnamurchan, etc., Memoir Geol. Survey Scotland, 1930, p. 100; *cf.* p. 82.

so constituted possesses remarkable properties. In particular, it is very sensitive to unequally distributed stress, the liquid part tending to be driven from places of greater to places of less stress. When in such a region an unequal distribution of crustal stress is maintained sufficiently long, there will be a continued flux of the interstitial magma, which will be driven out from areas of special disturbance to accumulate beneath areas of relative quiescence. If, in addition to this lateral displacement, the magma works its way into the upper crust or to the surface, highly alkaline rock-types may result. Otherwise, and more generally, the magma so displaced will go to impart a more or less marked richness in alkali to the crust beneath the undisturbed areas, and the effect may be seen only at some later epoch and in a less extreme manifestation.[1]

Thus, according to Harker, "intercrustal creep" away from the squeezed chamber of originally subalkaline ("calcic") magma is a necessary step in the emplacement of the alkaline rocks. In fact, he goes so far as to hold that "contemporaneous stress is proved by a certain horizontal differentiation [in an Irish granitic terrane]."

The wine-press idea has been adopted, as one of the essentials to a complete theory, by Benson, Bowen, Smyth, and others.

Smyth's Hypothesis.—Smyth states that fractional crystallization is one of the "extraneous agents" which "often play a minor role" in the generation of alkaline from subalkaline magma. He lays more stress on the volatile constituents, which "function through their capacity for combining with the elements characteristic of alkaline rocks, to 'yield mobile compounds which, from their distinctive physical characters,' tend to segregate as separate fractions."[2] How and when the alkalies are segregated is not made quite clear. While Harker and Bowen regard the alkaline magma as a purely residual liquid, wholly derived from, and due to the advanced crystallization of, a definite volume of magma, Smyth apparently assumes also the rise of gases from the earth's deep interior, quite independently of preliminary magmatic injection into the crust. A necessary condition for the segregation of alkaline magma is crustal stability,

. . . relative absence of movement. . . . As differentiation takes place only when the magma is partly liquid, or, rather, during the passage from liquid to solid by progressive crystallization, it follows that the longer this condition is maintained, the better the opportunity for completion of the process. If cooling is rapid, only basic rocks will result, having the composition of the primary magma; if slower, intermediate and acid differentiates will be pro-

[1] A. Harker, Pres. Address, British Assoc. Adv. Science, Portsmouth meeting, 1911, p. 6; Pres. Address, Quart. Jour. Geol. Soc., vol. 73, 1918, p. *lxix*, also p. *lxxvii*.

[2] C. H. Smyth, Proc. Amer. Phil. Soc., vol. 66, 1927, p. 561.

duced; while, if still slower, the ultimate products, alkaline rocks, will result. Slow cooling is favored by depth and by large masses of magma; thus, rapid transfer of magma up into cooler regions tends to prevent formation of alkaline rocks, unless the transferred magma is in large bodies, when, as a result of their slow cooling, after movement of the masses has ceased, alkaline satellites may be formed, as at Ice River.[1]

In contrast with Smyth, Harker assumes, as a principal condition for the formation of alkaline magmas, the squeezing-out and then horizontal migration of the residual alkaline liquid through scores or hundreds of kilometers. This magmatic movement implies the "downstream" fracture and correlated injection of the crust. Bowen also emphasizes movement of crust and magma, rather than their stability.

Such opposition of views arises because of the difficulty of explaining alkaline magmas by the differentiation of any liquid that is likely to be regarded as primary. In point of fact, all eruption of magma, alkaline or subalkaline, from the earth's interior clearly means crustal instability, while differentiation of alkaline from subalkaline magma demands some duration of relative quiet for the earth's crust.

Gillson's Hypothesis.—Gillson

> . . . believes that the process of albitization, now known to be a common accompanying feature of granitic intrusion, furnishes a key to the genesis of alkaline rocks. The passage of emanations rich in soda and alumina, which albitization phenomena show to have occurred, may in favorable instances have desilicated a granitic magma and so enriched it in soda and alumina that nephelite would crystallize, and after consolidation, soda-rich deuteric minerals form.

He adopts the idea of gaseous transfer of alkalies through liquid magmas. He does not explain why albitization itself takes place, nor why the albitizing solutions should ultimately become sufficiently poor in silica. In the words of Shand, Gillson's view fails "to account for the deficiency of silica which alone can cause felspathoids to be formed."[2]

Inadequacy of the Hypothesis of Differentiation from Pure Subalkaline Magma

The more or less contrasted hypotheses of Harker, Bowen, Smyth, and Gillson agree in assuming that the only material here involved

[1] C. H. Smyth, *op. cit.*, p. 571.
[2] J. L. Gillson, Jour. Geol., vol. 36, 1928, p. 471.

was primary and rule out assimilation of, or reaction with, country rocks. In any of its forms the hypothesis of differentiation from purely juvenile magma is not satisfying. Some of its troubles may be summarized.[1]

1. No pure differentiationist has brought his idea into agreement with a good general theory regarding the earth's constitution and thermal gradient, the origin of mountain chains, and allied, fundamental, thoroughly interwoven problems of geophysics and geology. Like the subalkaline magmas, the alkaline cannot be explained without preliminary answers to these hard questions. The pure-differentiation hypothesis demands that the parent subalkaline magma of each alkaline province was emplaced by simple injection, and that the injected body had large volume; for the alkaline liquid, being residual, was but a small fraction of the parent. Yet the largest observed intrusions—the subjacent—have clearly enlarged their chambers to some extent by replacing the country rock. The replacement means stoping in at least many cases. Does stoping lead to pure melting or assimilation in depth? To show that contamination of primary liquid in this way has been unimportant is at least as difficult as the absolute proof of abyssal assimilation on the big scale.

The refusal to credit the contamination in depth is due to doubt as to the thermal energy available in the subalkaline magma. Manifestly both latent heat and possible superheat together permit only moderate solution of foreign material. Yet in Chapter XIII we saw that even a comparatively small degree of contamination of a major subalkaline body may furnish the condition for the differentiation of a notable volume of alkali-rich liquid, the absolute volume of even a Pilandsberg, Ilimausak, or Kola mass not being too great. The pure-differentiation hypothesis calls for at least as great a disproportion between the volumes of parent subalkaline magma and daughter alkaline liquid and has no special advantage because of this quantitative relation.

Even at visible contacts, where contamination must ordinarily be much less advanced than at depth, there is plain evidence of significant incorporation of sedimentary material. An illustration is found in the voluminous "skarn" (silicated carbonate rock) inclosed by or inclosing eruptive masses. When the skarn was developed, nearly half of the metamorphosed rock disappeared in the form of carbon dioxide and water. Similarly the conversion of shales into hornfels means the expulsion of several per cent of water, carbon dioxide, sulphur compounds, chlorine, etc. Part, perhaps most, of these gases are expelled into the magma, becoming resurgent-magmatic.

[1] See also R. A. Daly, Jour. Geol., vol. 26, 1918, pp. 97–134.

Are these contaminating materials negligible in the problem of the alkaline rocks?

2. Harker's special form of the pure-differentiation hypothesis contains a questionable, though leading, postulate. He states that each "great liquid or mainly liquid reservoir within the crust . . . is doubtless incidental to the existence of much more extensive tracts of the lower crust in a semi-liquid state, that is, as a liquid crowded with crystals or a crystalline fabric with interstitial liquid." No explanation is given as to what is meant by "lower crust." Whether or not Harker here refers to material forming a transition from a holocrystalline crust to a noncrystalline substratum, it is doubtful that a sufficiently thick, crystal-sown liquid could exist for a period long enough to be the "theatre of long-continued igneous activity." Assuming the viscosity appropriate for the fractional-crystallization theory, as usually described, the crystals must ultimately separate because of differential density. Hence at no time would a great volume of mixed crystals and dominant liquid be expected in a cooling earth shell. A crystalline fabric containing interstitial liquid would be unstable, for such a mass would tend soon to squeeze out its own liquid, just as water is squeezed out from the lower layers of a thick deposit of mud.

Another difficulty with Harker's hypothesis: basalt, though a typical "calcic" magma, has often flowed out at the earth's surface when nearly or quite liquid.

Again, it is not easy to see how the semiliquid composite in the "lower crust" could be horizontally squeezed in such a way as to deliver "calcic" eruptives (extrusives and high-level intrusives) in a belt of mountain building and at the same time deliver alkaline eruptives to a region (foreland) adjacent to the mountain chain. Orogenic stresses are relieved in the belt; should, then, the foreland rocks be fractured to the extent of permitting horizontal "creep" of the residual liquid through long distances? In brief, Harker's conception might be more appealing if it could be shown to agree with a sound theory of the orogenic mechanism.

Other objections arise in connection with the actual distribution of rock types. For example, the foreland of the Cape Colony range was flooded with subalkaline plateau basalt immediately after the folding of the chain was completed.

3. The wine-press hypothesis has not yet been correlated with other major questions—the origin, mineralogical composition, and chemistry of the principal Archean part of the Sial. This greatest of all visible terranes is chiefly composed of granite, a rock which, according to Bowen, represents the direct magmatic parent of important

feldspathoidal types. Moreover, the terrane is also the locus of widespread, intense compression. Here especially, according to the hypothesis, we should expect to find feldspathoidal rocks in quantity. Yet these are remarkably rare among the older Pre-Cambrian formations.

The suggestion that such rocks, being derived from liquids of low density and therefore emplaced at high levels in the earth's crust, have been swept away by erosion is not a satisfactory explanation. Surface rocks and plutonic rocks alike were closely folded, upended, and depressed to great depths by Archean orogeny, and vast quantities of supracrustal and other originally high-level rocks still remain—visible—in the shields. Further, the shields seem not to have lost by erosion as much per square kilometer as some post-Cambrian cordilleras have lost—belts where feldspathoidal rocks do appear.

Smyth's version of the pure-differentiation hypothesis likewise suffers when confronted with the facts of Pre-Cambrian geology. So far as he relies upon the wine-press idea, his position is insecure for the reasons just given. However, Smyth lays more stress on the independent rise of "mineralizers," volatile components of subalkaline magma, "presumably of basaltic composition." The peerless development of pegmatites and the prevalence of lit-par-lit injection in the Archean clearly suggest the very special abundance of volatile emanations during the mighty events of early Pre-Cambrian time. Nevertheless, as we have seen, feldspathoidal rocks are not conspicuous members of the Archean complex.

4. Nor are those rocks as abundant among the post-Cambrian batholiths as they should be by the hypothesis considered. According to Harker, granitic liquid should have been squeezed out, into the foreland, by the orogenic wine press; yet as a rule the granitic rocks are actually found "upstream" from the foreland, within the belt of particularly intense, localized squeezing (see page 115). For Bowen the wine-press action becomes important only after the breakdown of the polysilicates has taken place in the residual liquid of the salic magma when nearly wholly crystallized. It is this residual liquid derived from a residual liquid that is squeezed into the crust below the foreland. Why is not the granitic liquid also moved into the same region? Harker speaks of "special circumstances" under which the migrating liquid becomes "alkaline," but he does not describe those circumstances; this is again to leave Hamlet out of the play. Nor is it easy to understand Harker's conclusion that the final liquid would produce an ultrabasic type of rock "such as an ijolite." The hydrolysis of feldspathic molecules, separating free silica, is not likely to give a solution of ijolitic character.

The following quotation from Shand is relevant:

Bowen suggests two ways by which the alkaline liquid may be freed from the excess of silica. One is by sinking of quartz crystals; the other, by the squeezing out of the residual liquid at a time "immediately preceding the period of marked resorption of quartz which is well attested in most rhyolites."

It is obvious that these processes are only possible on the assumption that quartz is a mineral of early crystallization in granites. Bowen has formerly contended that the true order of crystallization in deep-seated rocks is given by the study of the corresponding lavas, so his position is quite logical, for quartz is a mineral of early consolidation in rhyolites. But one is left wondering how to reconcile this view with the field evidence which, at every granite contact, shows that the residual liquor from granitic magma is invariably highly siliceous. I am not able to understand how *two* residual fluids, one highly acid and the other deficient of silica, can both be squeezed out of the same magma.[1]

The serious difficulty noted by Shand is not lessened if we accept Smyth's conclusion that the segregation of alkali-rich magma by juvenile gas is "on a large scale . . . compared with the formation of pegmatites, but analogous in principle."[2] Magmatic gas emanates in extraordinary quantity at many batholithic chambers where, however, feldspathoidal rocks are unknown.

Incidentally Smyth assumes the existence of "super-batholiths" with individual areas like those of Russia, the Mississippi Valley, and the Great Rift belt of Africa.[3] He gives no evidence to compel this revolutionary idea, or any suggestion as to why the earth's crust has been invaded by magma in this way, unexampled even in the greatest cordillera.

The Bushveld Complex of the Transvaal affords another test of the pure-differentiation hypothesis. Its tremendous flood of magma was differentiated to the point of producing hundreds of cubic kilometers of granitic liquid but did not produce feldspathoidal rocks. The celebrated alkaline masses of the Pilandsberg, Leeuwfontein, etc., are younger than the complex and belong to a different petrogenetic cycle.[4]

5. Many large basaltic volcanoes are threaded through with isolated pipes filled with phonolite, and yet these composites seem to

[1] S. J. Shand, Trans. Geol. Soc. South Africa, vol. 25, 1922, p. *xxvii*.

[2] C. H. Smyth, Proc. Amer. Phil. Soc., vol. 66, 1927, p. 573.

[3] C. H. Smyth, *op. cit.*, p. 578.

[4] See R. A. Daly, Bull. Geol. Soc. America, vol. 39, 1928, p. 714; also S. J. Shand's (Trans. Geol. Soc. South Africa, vol. 25, 1922, p. 96) section of the Leeuwkraal Complex—a foyaitic plug passing outward into foyaite porphyry and then on into phonolite, the whole being interpreted as a flattened extrusive dome resting on the eroded red granite of the Bushveld Complex.

lack quartz-bearing types of rock. Tahiti, Marquesas, and other mid-Pacific islands, with Jan Mayen, the Azores, Saint Helena, and Tristan da Cunha of the Atlantic basin, are examples. No explanation for the absence of quartz in the highly leucocratic differentiates is expressed or implied in Bowen's, Smyth's, or Harker's statement of origins. Holmes has raised the same objection to the hypothesis of Bowen, whose attempt to overcome the difficulty can hardly be called successful.[1] See page 472.

6. If feldspathoidal rocks result from the squeezing-out of residual liquors formed late in the crystal fractionation of basaltic magma, it does not seem possible to account for the chemical and mineralogical peculiarities of such mafic types as nephelite-bearing essexite, analcite basalt, nephelite basalt, leucite basalt, leucite basanite, and theralite.

7. Finally, the hypothesis in none of its forms explains adequately the common abundance of primary minerals rich in carbon dioxide or lime, or both, that are found in many species of the feldspathoidal class.

Derivation from Subalkaline Magma Modified by Syntexis

In view of the foregoing considerations, one may well sympathize with Fenner and others who have recently expressed doubt that mere fractional crystallization of any type of primary magma can account for all other igneous species, and with Erdmannsdörffer, who doubts that fractional crystallization of subalkaline magma can of itself explain the abundance of the volatile substances contained in strongly alkaline magmas.[2]

The apparent insufficiency of all forms of the pure-differentiation hypothesis has led to several alternative explanations, founded upon an essential amount of preliminary assimilation of foreign material by subalkaline magma, the contaminated solutions being differentiated into strongly alkaline liquid and complementary material.

Jensen Hypothesis.—The first suggestion along this line was made by Jensen, who imagined that beds of sulphates and chlorides of the alkalies were chemically deposited on the floor of the primitive ocean and afterwards deeply buried. He supposes these easily fusible salts to move upward along fault planes, on the way fluxing ordinary igneous rocks; the result is magma rich in alkalies. Many more or

[1] A. Holmes, Science Progress, vol. 11, 1916, p. 68. N. L. Bowen, Jour. Geol., vol. 27, 1919, p. 429.

[2] C. N. Fenner, Jour. Geol., vol. 34, 1926, p. 714. O. H. Erdmannsdörffer, Geol. Rundschau, vol. 7, 1917, p. 313. See also P. Niggli (Die Naturwissenschaften, vol. 44, 1916, p. 667), who believes much carbon dioxide and water to have been added to magmas by abyssal assimilation.

less obvious objections prevent petrologists from regarding the speculation seriously.[1]

Holmes Hypotheses.—In 1917, Holmes offered a quite different explanation. He assumed the existence of an eruptible peridotitic earth shell, underlying a crystalline basaltic shell, and also the intrusion of the peridotite into the basalt. Through their interaction the peridotite becomes desilicated, with the formation of orthopyroxenes. These crystals sink, "leaving above a magma relatively impoverished in silica, but enriched in alkalies and perhaps in a new series of volatile fluxes."[2]

For several reasons this hypothesis, covering feldspathoidal species in general, has not held its own in petrological thought. The existence of a general earth shell of peridotite, eruptible during the many periods when alkali-rich melts have appeared at or near the earth's surface, is itself highly doubtful, however the case may have been with rare invasions by molten peridotite. The assumed mechanism has not been, and to all appearances cannot be, correlated with the field associations of many feldspathoidal masses.

As we shall see, Holmes has found reason to modify the idea suggested in 1917 and now interprets some important leucitic types as differentiates of pure peridotitic liquid, and others as differentiates from its syntectics with rocks of basaltic "and perhaps even" granitic composition. So restricted, his idea is much less exposed to objection and deserves sympathetic examination.[3]

[1] H. I. Jensen, Proc. Linn. Soc. New South Wales, vol. 33, 1908, p. 491.

[2] A. Holmes, Quart. Jour. Geol. Soc. London, vol. 72, 1917, p. 273. This author has listed three possibilities for the generation of the nepheline-bearing rocks of Madagascar: (1) desilication of the original subalkaline magma by the water residual after advanced crystallization, (2) desilication by juvenile carbon dioxide, and (3) interaction of peridotitic liquid with basaltic material.

[3] H. G. Backlund (Bull. Geol. Inst. Upsala, vol. 24, 1932, pp. 10, 14, 15, 20, 22) speculatively finds the source of alkali-rich (soda-rich) magmas and rocks, not in the parental basalt of Bowen, but, if the author understands him aright, in a peridotitic "layer of the crust," thus accepting the essential hypothesis of Holmes. In some unexplained way material from the corresponding great depth is supposed to become of the agpaitic composition described by A. Fersmann (Abhand. prakt. Geol. etc., Halle, vol. 18, 1929, pp. 23–27). According to Backlund crystal fractionation of this agpaitic (elsewhere called ijolitic) liquid produces the alkali-rich intrusions, while, with Fersmann, he admits the possibility that the "miaskitic suite" may be explicable on the carbonate-syntexis theory. A concentration of the volatiles, including CO_2, is postulated, but these gases are, by hypothesis, purely juvenile. Unlike Bowen, Backlund believes that the volatiles of the agpaitic liquid must be concentrated in the highly femic residual liquid, the first minerals to separate (and rise because of the assumed high density of the parental liquid) being alkaline feldspars and nephelite. Among the products of the gas-rich, residual liquid are carbonatites and other "desilicated rock suites," all juvenile and erupted toward the end of the petrogenetic cycle. Since the feldspars and nephelite are segregated in the solid form, it is not easy to see how the patent liquidity of the highly sodic magmas can be explained by this mechanism.

Preferred Hypothesis.—A third form of the syntexis idea was first published by Daly in 1910, its statement being amplified in 1914 and 1918. Special points have been considered in other papers.[1]

The essential postulates are

1. Reacting magma subalkaline, ranging in composition from the basaltic to the granitic.
2. Its desilication (desaturation in silica) by:
   a. Assimilated carbon dioxide (from carbonate rocks) and water (from sediments in general).
   b. Assimilated lime and/or magnesia (from carbonatic rocks).
   c. Concentrated juvenile carbon dioxide, water, and other volatiles.
3. Differentiation of:
   a. The syntectics corresponding to 2a and 2b.
   b. Magma enriched in juvenile carbon dioxide, water, and other volatiles.

The resulting rocks are taken to represent the majority of feldspathoidal types.

Before 1910, the principle of desilication was seldom considered in petrological theories, and still its full importance cannot be declared. The problem is specially troublesome on its quantitative side, when the case for desilication by juvenile gases is examined. On the other hand, something has been done in the way of comparing facts of the field with speculative ideas about the effect of resurgent gases and assimilated sediments. The problem becomes yet more specific and less charged with uncertainties when limited further to the results of absorption of carbonatic rocks by subalkaline melts. The mineralogy and chemistry of many rock species suggested the hope that this restricted part of the problem might be cooperatively attacked by geologists and physical chemists. If the verdict was here to be adverse, it seemed clear that the whole idea would have to be given up as of little or no practical value. If, on the contrary, a part of the alkali-rich group of rocks could be shown to have originated through incorporation of carbonatic material, then the more elusive questions as to the effects of the assimilation of basic sediments other than carbonates, and the effects of the concentration of free carbon dioxide, water, and other volatiles could be examined with some hope of securing answers. In this broad field of inquiry the petrologist faces a whole army of difficulties. It has seemed to the author best to begin the attack along a limited section of the front line—a section where Nature had already provided some promising clues. For this reason the emphasis has been steadily

[1] R. A. Daly, Bull. Geol. Soc. America, vol. 21, 1910, pp. 87–118; *ibid.*, vol. 27, 1916, p. 328, and vol. 29, 1918, p. 463; Igneous Rocks and Their Origin, New York, 1914, Chaps. 19 and 20; Jour. Geol., vol. 26, 1918, pp. 97–134; *ibid.*, vol. 19, 1911, p. 315; Publ. 340, Carnegie Inst. of Washington, 1924, p. 116; Proc. Amer. Acad. Arts and Sciences, vol. 60, 1925, p. 70; *ibid.*, vol. 62, 1927, p. 70.

directed to limestone syntexis. What proportion of the many kinds of alkali-rich rocks are best explained as products of reaction between subalkaline magma and carbonatic rocks? If petrologists can ever answer that query satisfactorily, they will be in better condition to answer the very different question: What is the origin of the alkaline-rock group as a whole?

Among the facts pressing for explanation are the following:

1. The close association of alkaline and subalkaline rocks in the field.

2. The small individual and total volumes of alkaline bodies when compared with subalkaline bodies (see page 37).

3. The common association of nephelite syenite and some other important alkaline types with batholithic granite (itself taken to be largely a differentiate of syntectic magma; see Chapter XVII).

4. The abundance of lime-bearing and CO_2-bearing minerals in alkaline rocks.

5. The evidence of abundant volatiles, "mineralizers," in alkaline rocks, as shown by their commonly pronounced pegmatitic character.

6. The many cases where alkaline magmas have been erupted through basic—hydrous and carbonatic—sediments (see Appendixes C and D of "Igneous Rocks and Their Origin").

7. The failure of all attempts to connect alkaline bodies with any particular type of tectonic structure or with major areas, such as were formerly thought by some petrologists to warrant the names Atlantic suite and Pacific suite.

8. The objections to the pure-differentiation hypothesis, as applied throughout the feldspathoidal series of rocks.

These and other data led to the speculative conclusion that many alkali-rich magmas and rocks originate in eruptive subalkaline magma which had absorbed basic sediments or volatile substances (especially carbon dioxide and water or both) from the invaded terranes.

That part of the hypothesis which has to do with the reactions of carbonate rocks has been admirably stated by Shand. He points out that the assumed mechanism implies much more than the simple solution of lime in basaltic or granitic magma. Three distinct processes are involved:

> (1) Solution of limestone by magma, leading to direct formation of feldspathoids by desilication of felspar molecules: (2) Sinking of heavy lime-silicates and complementary rise of a light alkaline fraction under control of gravity; (3) Formation of alkaline carbonates and rise of these towards the roof of the magma chamber, where carbon dioxide is displaced by silica. . . . The operation of the third factor cannot be studied in the field on account of the disappearance of carbonic acid from the system, yet it is of much impor-

tance to the theory, for it provides an alternative method by which nepheline and other soda-rich minerals may be formed in the magma. . . .

Either sodium carbonate or sodium silicate may be generated by reaction between albite and calcium carbonate if an aluminosilicate of lime is formed at the same time. In the following equations it is assumed that a lime-garnet is formed.

$$2NaAlSi_3O_8 + 5CaCO_3 = Na_2SiO_3 + Ca_3Al_2Si_3O_{12} + 2CaSiO_3 + 5CO_2$$
$$2NaAlSi_3O_8 + 6CaCO_3 = Na_2CO_3 + Ca_3Al_2Si_3O_{12} + 3CaSiO_3 + 5CO_2$$

That such compounds as sodium carbonate and sodium metasilicate are actually generated in alkaline magmas is shown by the presence of cancrinite, pectolite, and other uncommon soda-rich minerals in many nepheline rocks. These light and very soluble salts must tend to rise, together with juvenile and resurgent fluids, towards the top of the magma-chamber. In doing so they may react with albite and anorthite molecules to give the further supply of nepheline, as follows:

$$NaAlSi_3O_8 + 2Na_2CO_3 = NaAlSiO_4 + 2Na_2SiO_3 + 2CO_2$$
$$CaAl_2Si_2O_8 + Na_2SiO_3 = 2NaAlSiO_4 + CaSiO_3$$

and even, when the temperature falls low enough,

$$CaAl_2Si_2O_8 + Na_2CO_3 = 2NaAlSiO_4 + CaCO_3.$$

Now although this discussion lacks a sufficient experimental or observational basis, it points to a very important conclusion, namely that under the operation of factors (2) and (3) *a body of highly alkaline rocks may be formed at a distance from any visible body of carbonate rock.* Thus the absence of limestone from the immediate neighbourhood of a felspathoidal rock cannot be regarded as proof that limestone played no part in its formation.

Shand estimates the amount of $CaCO_3$ necessary to desilicate a granitic magma so as to cause the replacement of one third of the feldspar by nephelite; the ratio is about 65:100. He proceeds:

Can a hundred parts of granitic magma supply sufficient heat to dissolve 65 parts of limestone? Certainly not, but perhaps a thousand parts or ten thousand parts can. It is necessary to remember that in a large number of well-investigated cases, foyaite bodies are just local facies of vastly greater bodies of granite or some other sub-alkaline rock, and that the temperature of the smaller mass may be maintained by the larger mass, in which case the difficulty of heat-supply simply does not arise. For instance, according to W. C. Brögger the eruptive rocks of the Kristiania district have a volume of 2,377 cubic kilometres, of which foyaite composes only 7 cubic kilometres or 0.29 per cent. H. S. Washington has estimated that the complex of Essex Co., Massachusetts, contains 63.6 per cent of granite, 33.4 per cent of diorite, and only 0.8 per cent of foyaite and essexite. In the Haliburton-Bancroft district of Ontario the granites cover 2,600 square miles, the foyaites only some 15 square miles, and W. G. Foye says that the total mass of the foyaites is "far less than one per cent of the total mass of the granites." . . .

I argue, then, that there is no theoretical objection to the proposition that a *large* body even of granitic magma may give rise to a *much smaller* body of felspathoidal magma by reaction with limestone. Since the foyaitic magma has a very low temperature of consolidation it will tend to be expelled into contraction-fissures or faults in the main mass of rock, or to be driven by escaping gases towards volcanic vents in the roof; thus there may be a concentration within a limited area of foyaitic magma which originated throughout a much wider area.[1]

Turning to the evidences at actual eruptive contacts, Shand asks:

What may reasonably be demanded in the way of proof? That every intrusion in limestone shall show a marginal facies of felspathoidal rock? Surely not, because the reaction is controlled by three highly variable factors, namely temperature, pressure, and gas-concentration, and perhaps geological structure, too; and also because a reaction that involves the liberation of carbon dioxide must be accompanied by strong convection currents in the liquid, which will tend to sweep the products of reaction away from the place where they were formed. In some cases there may be no reaction at all; in others, sodium carbonate or sodium silicate may be formed and carried away in solution; in others, a felspathoid may be generated as a temporary phase which is afterwards reabsorbed by the magma; and in other cases still the desilicated magma may be swept away from the contact region, to form an apparently later intrusion at a distance from the place where it was generated. It must not be forgotten that the contacts which we see to-day tell only part of the story; other chapters have been removed by erosion, or they may still await exposure. The absence of felspathoids from some limestone contacts, then, is without significance in comparison with their presence at others.[2]

Since 1910, a considerable number of petrologists have expressed approval of this form of the syntectic hypothesis in explanation of some highly alkaline rocks. Even Bowen and Smyth, while refusing to credit generation of important alkali-rich *magmas* through syntexis, agree that some *rocks*, usually grouped with the alkali-rich species, may have originated through the assimilation of limestone by alkali-rich liquids. Bowen further states that the desilication so produced and "the consequent production of feldspathoid molecules may well be supposed a reasonable possibility. Some alkaline rocks may, perhaps, be so generated."[3]

Partial acceptance of the hypothesis favored in this book is recorded by:

[1] The heat required for assimilation would be partly supplied if the invading magma had risen quickly from great depth, a condition suggested in Chapter XIII, for in that case the magma is somewhat superheated.

[2] S. J. Shand, Geol. Mag., vol. 67, 1930, p. 416.

[3] N. L. Bowen, Jour. Geol., vol. 23, Supp., 1915, p. 89. C. H. Smyth, Proc. Amer. Phil. Soc., vol. 66, 1927, p. 544.

Allan (Ice River).
Barth (Seiland).
Brogger (Fen district).
Brouwer (Java).
Du Toit (Marble Delta, Transvaal alkalines).
Eggleston (Cuttingsville).
Eitel.
Erdmannsdörffer (recognizes resurgent CO_2 and H_2O).
Gevers.
Guinsberg (Mariupol).
Hall and Molengraaff (Vredefort region).
Hatch and Wells.
Loewinson-Lessing
Loughlin (Tintic district).
Mennell.
Morozewicz.
Murray-Hughes (N. W. Rhodesia).
Niggli (?).
Pacák (Moravia).
Quensel (Almunge).
Rittmann (Ischia and Vesuvius).
Scheumann (Polzen).
Shand (feldspathoidal rocks in general).
Streckeisen (Ditro).
De Szádeczky (Ditro).
Tilley and Harwood (Scawt Hill).
Tyrrell (Trans. Faraday Soc., vol. 20, 1925, p. 425).
T. Vogt (Hortavaer).

Unfavorable to the hypothesis are: Bowen (in general), Cross, Fersman (Kola Peninsula), Geijer, Grout, Harker, Iddings, Kaiser, Lacroix, Lindgren, C. H. Smyth, J. H. L. Vogt, von Wolff, Washington, and Wiman.

Objections.—Through failure to understand the sediment-syntexis hypothesis, there has been considerable "lost motion" in its discussion.

1. A few petrologists have thought that the author assumes *basaltic magma to be practically the only kind* involved in the alkali-concentrating reaction with carbonate rocks and other sediments. Probably this mistake has arisen because the results of such reaction with basaltic magma were specially discussed in the earlier statements of the idea. That particular case was chosen to illustrate the principle, but granitic, dioritic, or other common kind of subalkaline liquid could have been similarly used. Although the thermal energy necessary for all eruptive action is largely derived from the Sima, the magmas reacting with sediments are, according to the general theory, diverse because there are different degrees of abyssal pure melting and assimilation and because of differentiation, whether of pure basalt or of its syntectics. For example, one may assume the vital reaction

to take place between carbonate rock and granite, no matter how this magma was generated—by pure melting of the Sial which had been stoped down into the substratum itself (the intrusive granitic liquid being somewhat superheated), or by differentiation from a basalt syntectic *in* the Sialic crust, or by ichor fluxing. In fact, the writer is inclined to agree with Shand, Bowen, Eskola, Loewinson-Lessing, and others in the view that nephelite syenites and their allies were in direct connection with granitic magma more commonly than with basaltic magma.

One of the latest among the many discoveries illustrating the point is the large-scale case described by Murray-Hughes and Fitch. The biotite granite of the great Hook batholith of northwestern Rhodesia passes marginally into augite granite, syenite, or granodiorite, and then into a "syenodiorite," richer in hornblende. This change is ascribed partly to assimilation of limestone, which everywhere forms the country rock of the lime-rich phases of the batholith. The evidence for assimilation is "ample." The crystallization of the lime-rich minerals gave residual liquid which ultimately crystallized as hastingsite granite, nephelite syenite, cancrinite syenite, and sodalite syenite. The associated migration of juvenile and resurgent gases led to the pneumatolytic development of scapolite, sodalite, and cancrinite in the country rocks. Calcite is a late-stage magmatic product in both the soda-rich and lime-rich groups of rocks.[1]

2. A second objection: the *visible hybrids* between limestone and subalkaline magma *are not alkaline rocks* but are actually poorer in alkalies than the adjacent uncontaminated igneous rock.[2] This is, of course, just what ought to be on the syntectic hypothesis. In general, the hybrid must have a lower percentage of alkali than the original magma, merely because of the addition of alkaline earths from the carbonate rock, if not also because the carbon dioxide and water, driven off, removed original alkali.

A specially telling example, at Scawt Hill, County Antrim, Ireland, has been studied skillfully and thoroughly by Tilley and Harwood. There the chalk is crosscut by a boss of normal olivine dolerite with nearly vertical contacts. Though a small mass, measuring about 300 by 200 meters, the dolerite was able to metamorphose and assimilate the chalk with quite remarkable results, including the desilication

[1] R. Murray-Hughes and A. A. Fitch, Quart. Jour. Geol. Soc. London, vol. 85, 1929, p. 109. Field relations do not support the contention of F. Loewinson-Lessing (Bull. soc. belge de géologie, etc., vol. 32, 1922, p. 65) that feldspathoidal rocks are essentially products of granitic magma alone.

[2] A. Meister, Sur les roches et les gisements d'or dans la partie sud du district d'Jenissei, St Petersburg, 1910, p. 641.

of the albite molecule to nephelite and the formation of aegirite. The chemical change of the igneous material, brought about by the reaction is shown by Table 61.[1]

TABLE 61.—ANALYSES OF ROCKS AT SCAWT HILL

	1	2	3	4	5	6
SiO_2	47 55	46.77	42 24	37 54	29.14	22 52
TiO_2	1 11	1 06	1 81	2 04	2 17	.57
Al_2O_3	16 18	14 93	13 16	13.39	10 46	10 11
Fe_2O_3	2.46	2 20	4 48	3.60	8.54	4 58
FeO	8.35	5.65	12 61	11.95	7.85	2.90
MnO	.16	.09	30	......	.34	
MgO	8.62	7 87	1.66	2.36	1 06	4 93
CaO	11.86	17 87	13 66	21.25	28 40	46 36
Na_2O	2.19	1 50	3 84	1.50	2.18	1.06
K_2O	.35	29	.78	.38	.19	.05
H_2O-	.42	.24	.48	.05	.41	.08
H_2O+	.80	1.72	4.48	5.71	5.17	.78
CO_2	.03	.16	.12	.20	3.02	5.08
Rest	.16	.30	.87	.64	1 16	86
Total	100.24	100 65	100.49	100 61	100 09	99 88

1. Olivine dolerite.

Endogenous contact zone, phases 2 to 5 inclusive.

2. Pyroxene-rich dolerite.
3. Nephelite dolerite.
4. Titanaugite-melilite hybrid rock or melilite-bearing nephelite dolerite
5. Melilite rock (hybrid zone).
6. Spurrite-merwinite-gehlenite-spinel (calcite) rock (metasomatized chalk).

In general, the loci of syntexis and of special alkalinization of the magma must be more or less widely separated. For this reason the limestone-desilication hypothesis cannot be discounted in the Bancroft region of Ontario by assuming that the nephelite syenites were there generated alongside of the limestone of the visible outcrop.[2] It is the very essence of the author's explanation that the alkalies have been transported with the aid of the resurgent gases well away from the primary locus of reaction. At Bancroft this is likely to have been at depth greater than the visible contacts of limestone and nephelite syenite. As Foye has shown in his valuable study of the district, the gas-rich, alkaline magma has moved not only up to the visible contacts but across them into limestone, converting the carbonate rock into amphibolite. He likens the combination of injected granite and limestone to a "gigantic steam-pack," from which the alkaline volatile solutions (magmas) were *expelled.*[3]

[1] C. E. Tilley and H. F. Harwood, Miner. Mag., vol. 22, 1931, p. 439.

[2] *Cf.* N. L. Bowen, Jour. Geol., vol. 23, Supp., 1915, p. 62.

[3] W. G. Foye, Amer. Jour. Science, vol. 40, 1915, p. 413; Jour. Geol., vol. 24, 1916, p. 783.

Among the many other available examples we note only a few of those recently described. Incipient wandering of the alkalies and volatiles at Scawt Hill explains the chemistry of the nephelite dolerite, with 4.62 per cent alkalies against only 2.54 per cent in the uncontaminated dolerite (see columns 1 and 3 of Table 61). The same principle seems to account for the anorthoclase-bearing vein in the dolerite near the edge of the hybrid zone (page 453 of the Tilley-Harwood memoir).[1] At the other extreme is the Rhodesian instance, where sodalite-bearing solutions appear to have risen from the Hook granite batholith at points many kilometers from the visible main contact.[2]

Conversely, alkali-rich magmas, formed by the syntectic process should not normally be rich in lime.[3]

3. Bowen and others appear to hold that the *resurgency* of the volatiles from the limestone and other sediments is for Daly *not essential*, being merely a "possible" accompaniment of the desilicating process. On the contrary, the resurgent gases are assumed to be vital in the genesis of alkaline magmas, where those gases are concentrated after the same "natural" manner as the "juvenile gaseous substances."[4]

4. Smyth supposes the author's explanation of alkali-rich rocks to be based upon *disbelief in fractional crystallization* and accordingly weak. To the contrary is an explicit passage in the 1918 paper, and this misapprehension is surprising in view of the author's long advocacy of fractional crystallization as one of the causes of differences among magmas and rocks.

5. Several petrologists have thought that the explanation offered for alkali-rich rocks relates to *reaction of subalkaline magma with limestones only*. That other kinds of sediments are involved has been

[1] It is difficult to catch the true meaning of the statement of Tilley and Harwood (p. 467 of their paper) that the Scawt Hill case should be "taken as an example of the restricted potentiality of igneous magma to generate alkali types by assimilation." Clearly assimilation was there restricted. Its potential effect under other conditions—larger masses of invading magma, deeper, hotter loci of reaction, different kinds of reacting magma, varying cooperation of connate water, etc.—is hardly to be estimated from Scawt Hill phenomena! Moreover, these naturally do not tell the full story of the chemical work done by escaping carbon dioxide. Thus one may well suspect the logic underlying the closing sentence of the memoir considered.

[2] R. Murray-Hughes and A. A. Fitch, Quart. Jour. Geol. Soc. London, vol. 85, 1929, p. 136. J. A. Allan (Mem. 55, Geol. Survey Canada, 1914, p. 127) found sodalite-cancrinite vein rock more than 8 kilometers from the main contact at Ice River, British Columbia.

[3] *Cf.* J. Stansfield, Assimilation and Petrogenesis, Urbana, 1928, p. 18. S. J. Shand (Trans. Geol. Soc. South Africa, vol. 34, 1931, p. 102) points out how, in general, essential data for the problem of the feldspathoidal rocks escape discovery with even the most intensive study of formations at the erosion surface.

[4] N. L. Bowen, Jour. Geol., vol. 23, Supp., 1915, pp. 65–66.

repeatedly indicated, in 1910 and later; Chapter XIX of "Igneous Rocks and Their Origin" was written to support the thesis that assimilation of non-calcareous rocks and of connate water should be considered a possible condition for the generation of many syenitic and other alkali-rich liquids.

6. Lindgren, Bowen, Vogt, Smyth, and Wiman have adversely criticised the limestone-syntectic phase of the general hypothesis because of the *abundance of the rarer elements*, such as the halogens, phosphorus, titanium, and zirconium in alkaline rocks. Each of these writers fails to see how such elements could be so concentrated from assimilated limestone.[1] It would, indeed, be astonishing if this were the actual cause of the concentration. But this test of the hypothesis is quite illusory. The rarer elements are, of course, assembled in the residual magma chiefly from the original subalkaline magma. The resurgent gases, like the juvenile gases, act as fluxing agents, tending to delay final freezing and to increase the proportion of rare elements in the residual magma, for the same reason as that obeyed by the juvenile gases. However, it is a question whether resurgent gases have not often been more efficient than the juvenile gases in "leaching" out rare elements from the original magma and segregating these elements in the alkaline mother liquor.

7. *Association with carbonate rocks.*—Turning from these more subjective grounds for doubting the sediment-syntectic hypothesis, we may well consider at some length a manifest lack in the evidence for that explanation of many feldspathoidal rocks. If valid, the hypothesis must be to a degree supported by the statistics of field association between these rocks and basic sediments. One phase of the test was discussed in the last chapter, dealing with the relation of hydrous non-calcareous sediments to the syenite clan, and will again be implied in a following section on the influence of resurgent water. Another phase of the statistical test, namely, the field association of strongly alkaline rocks with carbonate rocks, will now be discussed; it seems vital in the problem of most of the feldspathoidal eruptives. While here again the statistical evidence is not unfavorable to the general hypothesis, full corroboration is not yet in sight.

The first to stress this apparent weakness in the grounds for this hypothesis, the author compiled a fairly complete list of the districts which contain feldspathoidal rocks, noting those where calcareous

[1] W. Lindgren, Problems of American Geology, New Haven, 1915, p. 276. N. L. Bowen, Jour. Geol., vol. 23, 1915, Supp., p. 62. J. H. L. Vogt, Videns.-Skrifter, Oslo, Kl. I, No. 17, 1923, p. 32. C. H. Smyth, Proc. Amer. Phil. Soc., vol. 66, 1927, p. 548. E. Wiman, Bull. Geol. Inst. Univ. Upsala, vol. 23, 1930, p. 154.

rocks appear among the formations invaded by alkaline magmas. The list forms Appendix D of "Igneous Rocks and Their Origin." It is here omitted to save space but deserves present notice. The addition of later discoveries would not essentially change the statistical situation.[1]

Partly because of prejudice in favor of the pure-differentiation theory, many authors have furnished little or no information regarding the terranes invaded by the "interesting" feldspathoidal rocks. It needs no emphasis that the districts are exceedingly contrasted in area and petrological dignity. One may be listed because it contains a single dike of feldspathoidal or alkali-rich rock; another represents an extensive province covering hundreds of feldspathoidal bodies. To be thoroughly useful such a table should be quantitative and indicate the volumetric importance of each species in each district. The ideal cannot be closely approached until much more field work is done, but the table, even in its 1914 form, has value for petrological theory.

In all, 234 districts were listed. Seventy per cent of them have the association with carbonate rocks required by this particular phase of the syntectic hypothesis. When the table was constructed, care was taken to assume limestone below the surface of erosion only when the facts point strongly in that direction. Among the regions where there is reasonable assurance of this, despite the lack of outcrops of carbonate rocks around the feldspathoidal masses, are places like Beemerville, New Jersey (thick Kittatinny limestones and also Pre-Cambrian limestones in depth);[2] the Sweet Grass Hills [Paleozoic and Mesozoic (?) limestones in depth];[3] Winnett, Montana [Paleozoic and Mesozoic (?) limestones];[4]

Information about the nature of the country rocks is lacking for sixty-three districts. These are largely volcanic islands, the constitution of which, except at and near the surface, is unknown. Such cases are inconclusive until more facts are obtained regarding the hidden formations. Deep-sea volcanoes, like Kerguelen, Saint Helena, and Tahiti, may, of course, contain limestones interbedded, at depth, with their voluminous, dominantly basaltic lavas.[5] An actual illustration is found in Oahu, Hawaii, as proved by both surface outcrop and by

[1] *Cf.* S. J. Shand's table, Geol. Mag., vol. 67, 1930, p. 421.

[2] See M. Aurousseau and H. S. Washington, Jour. Geol., vol. 30, 1922, p. 571.

[3] J. F. Kemp and P. Billingsley, Bull. Geol. Soc. America, vol. 32, 1921, p. 437.

[4] C. S. Ross, Amer. Jour. Science, vol. 11, 1926, p. 226.

[5] Though opposed to the limestone-syntexis hypothesis for the feldspathoidal rocks of the Pacific, T. F. W. Barth (Amer. Jour. Science, vol. 21, 1931, pp. 515, 529) does consider the possibility of contamination of basaltic magma with coralline material as an explanation of a wollastonite-like mineral in a Necker Island "nephelitic basalt" or "phonolite" with nearly 8 per cent soda and 8 per cent lime.

deep borings. Yet the evidence from the sixty-three districts, though not negating, is negative.

On the other hand, a more serious result of the compilation immediately fastened attention. Nine, or 3.5 per cent, of the districts exhibit strongly alkaline rocks which are in such relations that the local absorption of carbonate rocks *seems* to have been impossible. These nine cases include Julianehaab, Cripple Creek, Red Hill (New Hampshire), Port Coldwell (Ontario), north-central Wisconsin, Auvergne (phonolites), Saxony (various phonolites), Kola Peninsula, and Mount Flinders (Queensland). A number of outstanding analogies have since been described. The significance of such cases will be described, with the conclusion that these occurrences are not irreconcilable with the syntectic hypothesis. Here one must take a risk: in the effort to steer away from the Scylla of dogmatism one may run into Charybdis—the reproach of special pleading. Yet it seems necessary to take the risk in trying to illustrate concretely that observed facts of each situation are not all the facts. Undoubtedly the cases considered will continue to represent difficulties for the limestone-syntexis hypothesis. Some of the occurrences already seem best referred to the effects of purely juvenile gas. Still others, including certain leucitic rocks, may have been evolved by a mechanism quite different from that involving the cooperation of substratum basalt. However, these exceptions to a statistical rule do not seem competent to undermine faith in a hypothesis which is so amply supported by the chemistry, mineralogy, and general field relations of the majority of feldspathoidal species.

Although an advocate of magmatic assimilation on a large scale, Ussing concluded that the limestone-syntexis hypothesis cannot apply at Julianehaab, on the ground that carbonatic formations are not exposed in the region. His conclusion is unavoidable if all required data were covered by the observations on the local geology. But were they so covered? In "Igneous Rocks and Their Origin" it was suggested that possibly carbonatic rocks of the Arsuk or other group had been stoped down and assimilated in depth, later yielding the foyaites, etc., by differentiation. But a more general question is involved: Is it possible that thick limestone masses, so common in the Archean shields, underlie the visible rocks of the Julianehaab region? The more adequately the Archean terranes of the world are studied, the more evident is their development by close folding, overthrust, underthrust, and lit-par-lit injection. By these processes, heavy masses of sediments and volcanics have been deeply buried, quite out of sight over extensive areas, though outcropping in the distance. The case is analogous to the deep burial of whole massifs under the nappes of the

Alps. Is there any doubt that the resulting stratigraphic surprises of the Alps would be matched in each Archean complex, if the structure were as well understood as that of Switzerland?

Shand has recently provided an eloquent parallel. The foyaite of the Spitz Kop, Sekukuniland (Transvaal), contains a large body of

FIG. 166.—Map of great inclosure of limestone in a foyaite-ijolite body cutting through the red granite of the Bushveld Complex. (*After S. J. Shand, Trans. Geol. Soc. South Africa, vol.* 22, 1924, *p.* 111.)

limestone, with which the foyaite has reacted (Fig. 166). Shand writes:

> Suppose that the Transvaal were as deeply submerged as South Sweden is [the region in which the analogous rock assemblage of Alnö is situated]. The Sekukuniland stock would then be situated in a large island of red granite, which would infallibly be interpreted as the top of a huge batholith, and the possibility of a thick limestone formation lying several miles beneath the granite would not be dreamt of. Yet that explanation happens to be the correct one, as the geological map of the Transvaal shows.[1]

(See Fig. 90.) Exactly the same situation is found in other cases of strongly alkaline rocks of the Transvaal, such as those of Leeuwfontein and Pilandsberg (Pilansberg). Like the Spitz Kop body, the parent magmas have there cut through the Great Dolomite, a thousand or

[1] S. J. Shand, Eruptive Rocks, London, 1927, p. 236.

more meters in thickness but invisible for long distances around each alkaline mass. In his memoir on the Pilandsberg, Shand writes:

No body of limestone is exposed anywhere in the Berg, and the foyaites contain little lime or magnesia. But the presence of cancrinite in many of the foyaites, and of calcite in the tuffs, show that carbonic acid was dissolved in the alkaline magma; and the outstanding fact remains that all the known foyaite occurrences in South Africa rise through thick limestones of the Transvaal and Nama systems. Thus if Pilansberg furnishes no proof of Daly's hypothesis, at least it presents no feature that is inconsistent with it.[1]

With Shand one may well regard Almunge as another analogy, just as Magnet Cove seems to be. Brögger explains the abundant carbonate rocks, so closely associated with the highly alkaline plutonics of the already famous Fen region, as derived from deep-seated Pre-Cambrian limestone, even though no such limestone outcrops anywhere near the Fen vents. Incidentally, whether one agrees with Brögger in regarding the sövites, rauhaugites, ringites, etc., as carbonatite and silico-carbonatite (igneous) rocks, or with Bowen who prefers a hydrothermal replacement origin for the visible carbonates, the facts are that the carbonates are *there*, in great quantity, and that it is no easier to attribute their accumulation to a purely juvenile process than to reaction with limestone in depth.[2] Deuteric or "hydrothermal" replacement of alkali-rich or feldspathoidal minerals is no proof that the rock containing these materials was not affected by earlier reaction of magma with carbonate.[3]

The celebrated Laacher See region offers further illustration of the necessity of caution in excluding limestone control because limestone does not appear in outcrops near alkaline eruptives. Although many types of feldspathoidal rocks have come out of the Laacher See vents, and although some bear primary calcite and other evidences of abundant carbon dioxide in depth, yet calcareous formations do not crop out in the vicinity. Until recently this fact seemed to militate decidedly against the syntectic hypothesis. However, Frerichs, in

[1] S. J. Shand, Trans. Geol. Soc. South Africa, vol. 31, 1928, p. 150.

[2] W. C. Brögger, Das Fengebiet in Telemark, Norwegen, Oslo, 1921, p. 357; N. L. Bowen, Amer. Jour. Science, vol. 8, 1924, p. 1, and vol. 12, 1926, p. 499.

[3] J. Phemister (Summ. Prog. Geol. Survey Great Britain, 1930, part III, p. 58) believes that his discussion of the carbonatized cromalite in the Loch Borolan laccolith disposes of the limestone-syntexis idea in that instance. S. J. Shand (Geol. Mag., vol. 67, 1930, p. 421) is not likely to agree, and it may be noted that J. J. H. Teall (*ibid.*, vol. 7, 1900, p. 390) was sympathetic with the syntectic hypothesis at Loch Borolan. It seems best to regard the question of origins there as wide open. Its full treatment would cover, among other things, the rather intriguing explanation of the "pseudo-leucites" in this body, by W. Eitel (Über die Synthese der Feldspatvertreter, Leipzig, 1925, p. 119).

1925, described fragments of crystalline limestone in the Devonian volcanics around Oberscheid. That author has hence deduced the presence of a limestone formation in the Rhenish Grundgebirge underlying the Devonian, which itself constitutes the floor of the Laacher See pyroclastics and lavas.[1] Suspicion that this is so is strengthened by Schuster's discussion of calcite-rich bombs in the Bell-Reiden area of the Laacher See district.[2]

Like the Julianehaab region the Cripple Creek district has been carefully mapped, and here also the limestone-syntectic hypothesis appears inapplicable. However, it is significant that the deeper mine workings among the alkaline rocks of Cripple Creek are quite seriously affected by the emanation of abundant carbon dioxide. Conceivably this gas may be purely juvenile and concentrated on an unusual scale. On the other hand, the deep-seated migration of sedimentary syntectics to the Cripple Creek vent is not impossible. The Rico, Leadville, Georgetown, Breckenridge, and other districts of western Colorado (all carrying syenitic, trachytic, or monzonitic rocks) show conditions favorable to the abyssal assimilation of thick limestones. The Tertiary updoming of the Front Range of the Rocky Mountains may well have involved subcrustal or intracrustal movement of magma toward the axis of the dome. Was this magma of syntectic origin and alkali-rich?

The intrusive stock at Red Hill, New Hampshire, is surrounded on all sides by orthogneiss. The nephelite syenite forms merely a local phase—a small part—of the stock. Both the orthogneiss and the younger stock cut the Montalban series of sediments, among which, according to Billings, are included carbonate rocks that had been metamorphosed into diopsidic types before the alkaline rocks of the state were erupted.[3] The sediments were intensely folded and downfolded before the intrusion of the orthogneiss itself. Can we exclude the possibility that the carbon dioxide, freed from the parent sediment during the regional metamorphism but remaining long trapped in depth, escaped into the Red Hill magma column and locally generated the nephelite syenite? On the other hand, can we exclude the hypothesis that this feldspathoidal rock was generated by the concentration of purely juvenile gas? As far as present information goes, the answer

[1] E. Frerichs, Centralbl. f. Miner., etc., 1925, Abt. A, p. 161.

[2] E. Schuster, Neues Jahrb. f. Mineralogie, etc., B.B. 43, 1920, p. 295. R. Brauns (Aus Natur und Heimat, 1926, sep. p. 38) remarks on the volume—*erstaunlich gross*—of carbon dioxide which still issues at the Laacher See vents. He (p. 28) believes that certain carbonate rocks of the volcanic complex are truly magmatic in origin and directly related to the accompanying calcite syenites and calcite pegmatites.

[3] M. P. Billings, Proc. Amer. Acad. Arts and Sciences, vol. 63, 1928, p. 77.

to both questions is in the negative. Thus Red Hill, like Port Coldwell (Ontario) and like each of the cases in Brazil, Lappland, etc., where field data are insufficient, cannot be regarded as a telling argument one way or the other.

Very different is the situation in the Hastings-Haliburton region of Ontario, in the Transvaal instances so well described by Shand, and at Ditro (Roumania). Whatever the origin of the limestone masses at Alnö, their partial solution in nephelite syenite magma, or in that from which nephelite syenite has been derived, is an objective fact (Fig. 167). Is it likely that the Italian alkaline lavas traversing the thick Mesozoic limestones and dolomites, now covered by flows and

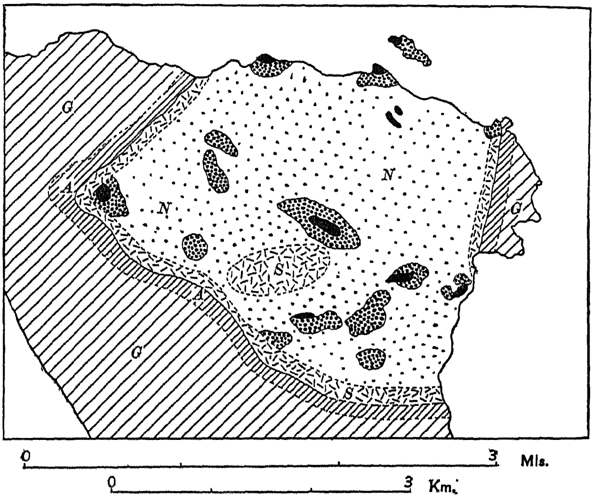


FIG. 167.—Map of part of Alnö Island. *G*, gneiss; *A*, metamorphic aureole in gneiss; *solid black*, limestone; *heavy dots*, limestone with nephelite syenite; *S*, syenite; *N*, nephelite syenite. (*After A. G. Högbom, Förhand. Geol. Fören. Stockholm, vol.* 17, 1895, *Plate* 2.)

breccias, did not in some cases react with the carbonates? Were the Montana and Arkansas magmas inert when they penetrated the thick limestones respectively underlying the exposed areas of feldspathoidal rocks? After field study, Landes concludes the Magnet Cove foyaite-ijolite mass to be a stock. At the outcrop it bears large volumes of crystalline limestone which Landes believes to have been carried up in the magma thousands of feet from their original sites in the lower Paleozoic systems. He also asks Shand's question, whether the ijolite and shonkinite at Magnet Cove were developed by reaction of foyaitic liquid with the limestone, but does not consider the origin of the foyaite itself.[1] Analogous is the Potash Springs stock of nephelite

[1] K. K. Landes, Amer. Mineralogist, vol. 16, 1931, p. 313.

syenite and its allies in the neighboring part of Arkansas. This stock is cut by many veins of calcite, has a phase called "wollastonite rock," and carries melanite, another significant mineral.[1] The Arkansas stocks illustrate once more the fallacy of judging the value of the syntexis idea merely in terms of observations at the outcrop. Before final judgment is reached, one must know whether van der Gracht is right in his contention that the whole deformed mass inclosing the stocks was thrust bodily over the extraordinarily thick limestones of the Ouachita foreland. In that case we should have to reckon with much more limestone than that appearing merely in the terranes visible around Magnet Cove and Potash Springs and to the northwest.[2]

Among the feldspathoidal bodies discovered since 1914, and listed among those that seem to have no direct relation to carbonate rocks or other basic sediments, is a Pre-Cambrian "batholith" of syenite, with nephelite-rich phases, described by Cooke. Carbonate rocks do not outcrop in the vicinity. In the adjacent Larder Lake area are great bands of ankeritic rocks; these were "dolomitized" by juvenile emanations from a large intrusive body of magma, "probably syenite"[3] (see below).

Like Brögger at Fen, Högbom at Alnö (Fig. 167), and Quensel at Almunge, Guinsberg at Mariupol believes it best to assume deep-seated limestone syntexis in order to account for the nephelite syenite of his field, even though limestone does not form outcrops in the immediate vicinity. It is worth noting that the feldspathoidal rock is transitional, through alkaline syenite, into granite.[4] So also Brown suggests the possible occurrence of limestone at depth in order to account for the highly varied alkaline types in the Mount Dromedary district, New South Wales, even though no outcrop of limestone is known within a radius of 80 kilometers from the intrusive complex.[5]

[1] E. R. Lloyd, Hot Springs folio, U.S. Geol. Survey, 1923, p. 7.

[2] W. van der Gracht, Verh. kon. Akad. Weten. Amsterdam, Afd. Nat., Deel 27, No. 3, 1931.

Is it accidental that the groundmass of the sills and pipe breccias in central Arkansas is largely calcitic, while the sills are monchiquitic and ouachititic, and the breccias inclose fragments of alkaline syenite and nephelite syenite? See C. Croneis and M. P. Billings, Jour. Geol., vol. 37, 1929, p. 542.

[3] H. C. Cooke, Mem. 131, Geol. Survey Canada, 1922, p. 48.

[4] A. S. Guinsberg, Annales Inst. Polytech. Pierre le Grand, Petrograd, vol. 1916, p. 433.

[5] Ida A. Brown, Proc. Linn. Soc. New South Wales, vol. 55. 1930, p. 637. This fine monograph describes a series of rocks remarkably like those of the Highwood and Little Belt Mountains of Montana, Loch Borolan, and the Fen region. The melanite-bearing species of Mount Dromedary recall the skarn phases of thermally metamorphosed limestone; carbon dioxide was one of the volatiles and primary calcite is of some volume among the accessory constituents.

8. The offered hypothesis is far from implying that alkali-rich magmas must be *generated wherever subalkaline magma traverses limestone* or *other basic sediment.* That condition of itself is, of course, quite inadequate. Notable assimilation at visible contacts is relatively rare, in post-Archean terranes at least.[1] Assimilation of importance, demanding high temperature among other things, is generally restricted to depths greater than those reached even by prolonged erosion. It is favored by shattering of the crust rock, and subsidence of xenoliths. Thus Eskola found that the magma of sviatonossite (a lime-rich and alkali-rich rock allied to malignite) reacted but little with the intruded limestone at main contacts, while, on the contrary, there was drastic reaction with limestone xenoliths, which were converted into typical skarn rocks. Doubtless one reason for the contrast was the greater chilling at the main contacts. According to Eskola, assimilation of the limestone was preceded by the formation of skarn; "assimilation of the skarn presents itself as a consequence of magmatic stoping."[2]

Bastin and Hill found little visible evidence of the attack of monzonitic magma on limestone of the Evergreen Copper Mine district, Colorado, but assumed this process to have taken place in depth, in order to account for a phase of the monzonite bearing garnet and wollastonite.[3]

Eckermann has briefly discussed the reason for the sporadic nature of the assimilation at contacts with limestone. Unlike Eskola, who thinks that this "depends upon mechanical conditions, namely, the folding and mixing of crushed materials," Eckermann finds the principal condition for assimilation in the magma's retention of the carbon dioxide formed during the crystallization of the skarn minerals. He further suggests the development of alkaline rocks at volcanic vents by the passage of the gas through the vents.[4]

[1] *Cf.* P. Eskola, Jour. Geol., vol. 30, 1922, p. 294; H. von Eckermann, Medd. Stockholms Högskola Mineralog. Inst., No. 43, 1923, p. 530.

Eskola (Comptes Rendus Soc. Géol. Finlande, No. 3, 1930, p. 34) notes the presence of great masses of Pre-Cambrian limestone in Transbaikalia and concludes that, if the limestone-syntexis theory of some alkaline rocks were valid, "alkaline rocks should occur in the Transbaikalian shield, if anywhere." As noted above, in the text, this statement can hardly be defended. As a matter of fact, Nature did succeed, according to Eskola, in assembling all the necessary conditions at Sviatoy Noss, Transbaikalia, so that there granitic magma reacted with limestone, giving the alkaline sviatonossite as a product.

[2] P. Eskola, Finska Vetens.-Soc. Förh., vol. 63, 1920–1921, Afd. A, No. 1, p. 93.

[3] E. S. Bastin and J. M. Hill, Econ. Geol., vol. 6, 1911, p. 465.

[4] H. von Eckermann, Geol. Fören Förh. Stockholm, vol. 45, 1923, p. 531.

9. The objection that feldspathoidal rocks are generally *associated with calcareous sediments, merely because these seldom fail on continental plateau or ocean floor,* can be answered in the same way as the analogous objection for the hypothesis when applied to the syenite clan. A few examples will illustrate the fallacy of the objection.

The Livingston (Montana) folio of the United States Geological Survey shows the Tertiary theralites and allied rocks only in the area underlain by thick limestones. Elsewhere the limestones had been eroded away before the Tertiary eruptions began and there these furnished only subalkaline species.

In Java and Madura the early Tertiary lavas (all subalkaline) penetrated a terrane devoid of important calcareous beds. After the thick Miocene limestone was deposited along the northern coast of Java, it was traversed by new eruptives, largely alkali-rich. Of particular interest is the recent discovery of shells of trachytic and phonolitic rock around limestone blocks inclosed in the lava dome of Merapi Volcano, Java. This pyroxene-andesite magma developed in the limestone wollastonite, diopside, garnet, anorthite, and epidote. One of the larger xenoliths was found to be zoned, layers charged with the lime-silicates being adjoined by others bearing leucite and by still others described by Brouwer as trachyte and leucite phonolite. Both of these alkaline rocks carry calcite, apparently primary. The manner in which the strongly contrasted zones were developed around the limestone block is by no means obvious, but the association is significant in connection with the general problem of alkaline rocks.[1]

The Paleozoic eruptives of Bohemia are all, as far as known, subalkaline—diabases, diorites, granites, etc. Only after the Tertiary limestones were deposited over the region and igneous activity renewed, were the phonolites and their allies erupted. Bohemia contains an alkaline province now, but it contained none in the Paleozoic era.

10. The syntectic hypothesis has been adversely criticized on the ground that, *if a magma assimilates, it must be omnivorous,* desilication by limestone being offset by the silicating effect of siliceous rocks, always associated and likewise necessarily assimilated. However, observation shows that granitic magma, for example, reacts much more easily with carbonate rock than, say, with orthogneiss. Differential assimilation of invaded rocks has been often described, as recently by Read, who has so ably and thoroughly studied the relative contamination of the gabbro magma of Arnage by argillaceous and quartzitic sediments.[2] In Finland Eskola has observed a number of

[1] H. A. Brouwer, Jour. Geol., vol. 36, 1928, p. 545; Kon. Akad. Weten. Amsterdam, Proc., vol. 31, 1928, p. 492.

[2] H. H. Read. Quart. Jour. Geol. Soc., vol. 79, 1923, p. 460.

instances where pegmatitic magma performed differential assimilation. Each "pegmatite, cutting through limestone and other rocks as well, has developed much diopside and titanite only while intersecting the limestone, but is an ordinary mica pegmatite outside of the limestone."[1] A parallel case is found in the Bushveld Complex, where big masses of shales seem to have disappeared in solution, while associated quartzites of comparable volume remained as xenoliths in the norite-granite magma.[2] It must be remembered that the volatile part of the sediment is, by hypothesis, specially concerned with the formation of alkaline magma. As far as this essential part of the mechanism is concerned, can there be any doubt of the difference of effect wrought by limestone as against quartzite or orthogneiss? The carbonate gives resurgent mobile gas incomparably more abundant than that which could be furnished by any ordinary siliceous rock, supposed to be assimilated. That magmatic reaction and solution affect varied country rocks at different rates seems to be as inevitable as differential metasomatism in zones of contact—a well-ascertained fact.

A suggestive analogy is found in the different rates of reaction of different carbonates in contact metamorphism. Thus, for example, the somewhat argillaceous dolomite of the Granitberg, South West Africa, suffered dissociation of its magnesium carbonate, with the formation of forsterite, spinel, and free carbon dioxide, while the accompanying calcium carbonate was not affected by the magmatic heating. The contrast of behavior of the two carbonates may be due to the considerable difference of their temperatures of dissociation.[3]

[1] P. Eskola, Jour. Geol., vol. 30, 1922, p. 291.

[2] See R. A. Daly, Bull. Geol. Soc. America, vol. 39, 1928, p. 755. Similar differential solution of clay slate and quartzite was noted by O. H. Erdmannsdörffer (Jahrb. geol. Landesanst., 1911, II, p. 368). *Cf.* W. H. Collins, Mem. 95, Geol. Survey Canada, 1917, p. 54.

[3] E. Kaiser, Die Diamantenwüste Südwest-Afrikas, Berlin, 1926, vol. 1, p. 267. Though Kaiser explains cancrinitic phases of the Granitberg nephelite syenite by reaction with the adjacent dolomite, he does not believe that syntexis of carbonate rock was involved in the generation of the nephelite magma itself.

According to W. Manchot and L. Lorenz (Zeit. f. anorg. Chemie, vol. 134, 1924, p. 315), dry $MgCO_3$ is completely dissociated at atmospheric pressure and 540°. The corresponding temperature for $CaCO_3$ and for dolomite is about 900° (T. Kato, Japanese Jour. Geol. and Geog., vol. 6, 1928, abstr. p. 1; C. S. Garnett, Miner. Mag., vol. 20, 1923, p. 54). At 150 atmospheres of pressure and at ignition temperature, the $MgCO_3$ of dolomite is dissociated to MgO and CO_2, while the $CaCO_3$ is recrystallized. So predazzite, a mixture of $CaCO_3$ and MgO, has been explained (see H. E. Boeke and W. Eitel, Grundlagen der phys.-chem. Petrographie, Berlin, 2d ed., 1923, p. 520).

Of course, the differential assimilation of carbonates is not controlled merely by temperatures of dissociation. Thus, according to T. Barth (Norsk Geol.

Evidently the idea that an assimilating magma must be omnivorous is quite without justification.

Abundance of Gases.—The remarkable variability and coarseness (pegmatitic habit) of grain of many alkali-rich intrusives is an impressive fact. A few examples will suffice: in the Pilandsberg, Leeuwfontein, and Vredefort masses of South Africa; in the Seiland and Fen bodies of Norway; at Almunge, Sweden; among the analcitic rocks of Moravia; in the Hastings-Haliburton field of Ontario; at Litchfield, Maine. The clear analogy with mineral-vein deposits and with quartz-bearing pegmatites has long held petrologists to credit an extraordinary richness of alkaline magmas in volatile material. Every published explanation of these magmas assumes that some of the dissolved gas is juvenile; the important question is: in what ratio to the total gas?

The list of authors who have recently insisted upon the necessity of paying at least some attention to *resurgent* gases in the question of magmatic origins might be greatly extended if the names of all assimilationists were included, for manifestly assimilation involves the principle of resurgency. For the theory of the alkaline magmas the question is one of *scale*, and one must keep steadily in mind the relative insignificance of feldspathoidal bodies as to volume when compared with subalkaline bodies. The juvenile gas of the parent subalkaline injection may have many times the mass of any absorbed foreign gas, and yet it may be the latter which is most active in segregating the strongly alkaline magma in the great chamber.

We have already noted that resurgent water and carbon dioxide, though originally connate in sediments or volcanics, may have been freed from these during regional metamorphism and temporarily collected elsewhere in the crust. Later these gases may become absorbed in injected subalkaline magma, which indeed, may be incapable of assimilating the residual rock of the regionally metamorphosed formation whence the gases were derived.[1]

Purely *juvenile* volatiles also are concentrated locally, in the crust. Either by ordinary pneumatolysis or by regional metamorphism of igneous crust rocks, juvenile solutions are, as it were, distilled into bodies of overlying rocks. Bruce and Hawley have given an illustration. The greenstones of the Red Lake district, Ontario, have been carbonated to a remarkable degree. One phase carries 27 per cent carbonates and 9 per cent hydromagnesite by weight. The authors

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Tidsskrift, vol. 9, 1926, p. 300), the assimilation of dolomite by a hot basic magma causes the precipitation of $MgSiO_3$ (in bronzite, for example), with a corresponding enrichment of the liquid with CaO and CO_2.

[1] *Cf.* T. Barth, Norsk Geol. Tidsskrift, vol. 9, 1926, p. 301.

regard this metasomatism as deep-seated and it may well have been due to the upward migration of purely juvenile solutions.[1] Similar carbonation, probably caused by revivified juvenile and perhaps resurgent volatiles, is very common among the older basic lavas of the world. In the Larder Lake district of Ontario (a locus of Pre-Cambrian nephelite syenite) Cooke found the Keewatin basalt, Timiskaming basalt, black slate, conglomerate, and diorite porphyry all to have suffered carbonation by juvenile solutions. The resulting carbonated bodies of rock have "enormous volume" and Cooke emphasizes the great size of the parent reservoir of magma from which "such huge quantities" of carbon dioxide were exhaled.[2]

In view of these and many similar observations, must we not suspect that juvenile carbon dioxide as well as resurgent carbon dioxide may have been essential in the development of some feldspathoidal rocks? Perhaps here is the secret of the assemblages of types in the Kola Peninsula, the Julianehaab district, etc.

Failure of important carbonatic formations among the country rocks of the great feldspathoidal bodies in the Kola peninsula is about as absolute as at Julianehaab. Yet the possible existence of limestone or dolomite in depth is suggested by the recent discovery of "pneumatolytic and hydrothermal calcitites" in all three series of monchiquitic, alnöitic, ijolitic, turjaitic, syenitic, and nephelinitic dikes at Cape Turij. In any case the Kola magma was at least locally rich in carbon dioxide.[3]

[1] E. L. Bruce and J. E. Hawley, 36th Ann. Rep. Bur. Mines, Ontario, 1928, pp. 11–13. J. F. Wright (Summ. Rep. Geol. Survey Canada for 1927, part B., p. 69) gives another good illustration of this profound alteration of the Canadian greenstones. So it has been with those of Rhodesia (A. M. Macgregor, Bull. 11, Geol. Survey Rhodesia, 1928, pp. 15, 68).

[2] H. C. Cooke, Mem. 131, Geol. Survey Canada, 1922, p. 48.

[3] D. S. Beljankin and V. I. Vlodavec, Travaux Petrog. Inst. Acad. Sciences, Leningrad, vol. 2, 1932, p. 71.

A. Fersman has remapped the alkaline rocks of the Kola Peninsula. Though he has added many valuable data regarding their differentiation, he is baffled by the question of the generation of the original magma (Urmagma), merely stating that carbonate syntexis is probably not to be considered in this case, since no important mass of limestone is known in the region. Nevertheless, he notes that certain of the rock types are "rich in calcium due to its assimilation by the walls of the channel up which the magma rose." The nature of the wall rocks of the channel is not described. Pectolite and cancrinite are recorded as crystallized products of the assimilation (see A. Fersman, The Khibine and Lovosero Tundras, part 2, English abstract, Moscow, 1929, p. 3; Geochemische Migration der Elemente, Abhand. prak. Geologie, etc., Halle, vol. 18, Teil 1, 1929, pp. 36, 54). E. H. Kranck (Fennia, vol. 51, No. 5, 1928, p. 83) prefers to think the Kola alkalines are pure differentiates of primary magma. On the other hand, W. C. Brögger (Das Fengebiet, Christiania (Oslo), 1921, p. 382) writes concerning the alkali-rich

Then, too, the emanation of gases directly from primary magma, without temporary retention in the crust, is to be considered. Their alkalinizing effect seems to be the basis of Brauns' explanation of the Laacher See rocks.[1]

Chemical Effects of the Absorption of Carbonate Rocks.—Experiment has not yet shown in detail the influence of the assimilation of carbonate rock on subalkaline magma. The contrast of the effects respectively wrought by dolomite and pure calcium carbonate needs special examination. However, it is worth while to glance at some of the chemical data, imperfect though they are.

The carbon dioxide freed by magmatic heat and reactions is a powerful flux. With increase of fluidity and entrance of the new components any initial tendency to magmatic differentiation is strengthened; hence we can understand the remarkable capacity of alkali-rich magma to differentiate.[2]

The calcium oxide introduced into a somewhat superheated magma inoculates the solution and causes early separation of lime-bearing crystals, thereby making the residual liquid more alkaline than it would have been without the contamination. If the new molecules are diopsidic—a common case—the foreign lime binds at least 2.5 times its own weight of silica. Other molecules would have the same desilicating effect. In consequence feldspathoids take the place of at least some of the feldspar that would otherwise have crystallized. Since magnesia and iron oxide accompany the foreign lime into the augite and other early-formed crystals, the residual liquid should be less ferromagnesian as well as less calcic than the original magma.[3]

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rocks of Turja, also in the Kola region: "The occurrence of a melilite-rich rock like turjaite shows that in the Turja district also the eruptive magma must have been mixed with assimilated limestone (or with carbonatite magma)."

[1] R. Brauns, Centralbl. f. Mineralogie, etc., 1926, p. 8; Aus Natur und Heimat, 1926, pp. 28, 38 (the best summary of Laacher See petrology). This author accounts for the carbonate of the Laacher See *Calcitsyenit, Calcitpegmatit, und Carbonatit* as primary crystallizations, due to the reaction of juvenile carbon dioxide with magmatic calcium, alkali-rich rocks being another product of special concentration of the gas. It is significant that, notwithstanding the length of time since the Pleistocene eruptions, this district is still characterized by the steady voluminous emanation of carbon dioxide (but see also p. 510).

[2] See T. Barth's clear statement (Norske Videns.-Akad. Oslo, Kl. I, 1927, No. 8, pp. 115–116).

[3] *Cf.* P. Niggli, Trans. Faraday Soc., vol. 20, 1925, p. 438. We have seen reason to credit superheat in even granitic liquid, if this was the product of pure melting at great depth. In any case the syntexis idea seems able to account for the common field association of granite with nephelite syenite, the most important of the feldspathoidal types. T. W. Gevers (personal communication) has studied eruptive rocks of the Auas Mountains, South West Africa and there found "con-

Niggli has studied several chemical systems involving carbonates. In a 1916 report on one of these researches he wrote (in translation):

The investigations already permit insight into the processes resulting from the assimilation [*Einschmelzung*] of carbonate rocks by magma—processes which according to R. A. Daly are important in the differentiation of rocks. For example, if at the pressure of one atmosphere (without escape of CO_2) calcite is dissolved [*eingeschmolzen*] in a melt rich in $K_2Si_2O_5$, then Ca_2SiO_4 is crystallized and simultaneously the residual melt becomes richer in K_2CO_3 and silica-poorer silicates, e.g., K_2SiO_3. The condition favorable to equilibrium of the silicates is therefore displaced, at the cost of the strongly siliceous [*silizifierten*] forms, in the alkali direction [*nach der Alkaliseite*].[1]

Passages of his well-known monograph on magmatic volatiles reiterate Niggli's belief that the assimilation of carbon dioxide, water, etc., is important in fixing new conditions of equilibrium in magma; and that such resurgent gases play "a quite important [*erhebliche*]" role in the formation of migmatites and resulting differentiates.[2]

Presumably the influence of resurgent gases on the course of crystallization and differentiation is like that exerted by the same gases when of juvenile origin. Bowen has indicated the molecular complexity of the residual liquid rich in the juveniles. The most important of the equilibrium reactions in the liquid

. . . involve the breakdown of part of the polysilicate molecules as follows:

$$KAlSi_3O_8 = KAlSiO_4 + 2SiO_2$$
$$NaAlSi_3O_8 = NaAlSiO_4 + 2SiO_2$$

There must also exist such equilibria as the following:

$$NaAlSiO_4 + H_2O = HAlSiO_4 + NaOH$$
$$KAlSiO_4 + H_2O = HAlSiO_4 + KOH$$

and, doubtless,

$$NaOH + HCl = NaCl + H_2O$$
$$2NaOH + H_2S = Na_2S + 2H_2O$$
$$2NaOH + CO_2 = Na_2CO_3 + H_2O$$

with similar reactions for the corresponding potash compounds, besides very complicated equilibria between the molecules S, SO_2, SO_3, C, CO, CO_2, H_2S, H, H_2O, O, HCl, Cl, etc.[3]

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vincing evidence" of limestone-desilication of magma, with the formation of feldspathoids and also primary calcite (in analcite basalt).

[1] P. Niggli, Zeit. f. anorgan. Chemie, vol. 98, 1916, p. 308; see also especially p. 321.

[2] P. Niggli, Die Leichtflüssigen Bestandteile im Magma, Leipzig, 1920, pp. 123, 202. *Cf.* P. Niggli, Verh. Schweiz. Naturf. Ges., 1920, sep. p. 14, and Trans. Faraday Soc., vol. 20, 1925, p. 438.

[3] N. L. Bowen, Jour. Geol., vol. 23, Supp., 1915, p. 44.

The concentration of water thus leads to action comparable with hydrolysis.

We have no complete, authoritative list of reactions and molecular results to be expected when resurgent carbon dioxide is added to the residual magma. That carbonates of the alkalies would be formed in the liquid is suggested by a reaction deduced by Eitel and, according to Barth, actually represented in Nature:

$$CaCO_3 + Na_2Al_2Si_2O_8 = Na_2CO_3 + CaAl_2Si_2O_8.$$

Incidentally the same reaction would help explain the development of anorthite and other calcic plagioclase, with scapolite, where the alkali-rich pegmatites of Mansjö (Sweden) have absorbed some of the intruded limestone.[1]

Giorgis and Gallo have described an experiment of present interest. They immersed three analyzed samples of Vesuvius lava in water and for two months kept a current of CO_2 passing through the mixture. At the end of the time the lavas were found to have lost 30 to 40 per cent of their soda, the amounts of the other constituents being little changed.[2]

Specially significant is the already quoted statement by Shand, whose experience in chemical petrography gives weight to his opinion (see page 498).

Since assimilated lime tends to bind silica in the form of non-aluminous silicates, it is reasonable to ask whether alumina is freed, to crystallize as corundum or to form spinels and other aluminates. Corundum does appear in nephelite syenites cutting limestones of Ontario, India, etc. The Montana sapphires, along with nephelite, are found in minette dikes cutting thick limestones (Fig. 98). According to Jensen, corundum is a constituent of the melilite basalt of the Warrumbungle Mountains, New South Wales.[3] Plumasite, the oligoclase-corundum rock, may be an analogy.[4]

Brauns and Uhlig write a reaction whereby nephelite results from a combination of the albite molecule with "freed and independently moving alkali-aluminate," thus:

$$3NaAlSiO_4 = NaAlSi_3O_8 + Na_2Al_2O_4.*$$

[1] W. Eitel, Tschermaks Min. und Petr. Mitt., vol. 38, 1925, p. 10. T. Barth, Skrifter Norske Videns.-Akad. Oslo, Kl. I, 1927, No. 8, p. 72. H. Von Eckermann, Geol. Fören. Forh. Stockholm, vol. 44, 1922, p. 203.

[2] G. Giorgis and G. Gallo, Gazetta, vol. 36, 1906 (*i*), p. 137. *Cf.* O. Pacák, Bull. internat. Acad. Sci. Bohême, 1926, p. 89.

[3] H. I. Jensen, Proc. Linn. Soc. New South Wales, vol. 32, 1907, p. 615.

[4] A. C. Lawson, Bull. Dept. Geol. Univ. California, vol. 3, 1903, p. 219.

* R. Brauns and J. Uhlig, Neues Jahrb. f. Mineralogie, etc., B.B. 35, 1912, p. 212.

Fenner has synthesized nephelite and analcite by using aluminate of soda as one of the raw materials.[1] Niggli emphasizes the importance of aluminates of the alkalies in the generation of the alkali-rich rocks, the presence of these compounds being dependent upon a sufficiently low content of silica.[2] Shand accepts the desilication of albite and the migration of its constituents in the form of sodium aluminate.[3] Goodchild thinks that aluminates of the alkalies exist as such in the magma and act as independent units in differentiation.[4]

The extensive feldspathization of quartzites immersed in the magma of the Bushveld Complex is explicable by assuming the presence of abundant alkali-aluminates in the solutions entering the quartzite from the magma.[5] According to Goldschmidt, the alkalinization of invaded schists by certain Norwegian magmas was caused by sodium silicate, "water glass," in the emanating solutions; yet he states that some syenitic rocks may be formed metasomatically by the transfer of nephelite or alkali-aluminate into older, invaded granite.[6]

Thus of late years the suspicion has been growing among petrologists, that the alkali-aluminates may be essential in some forms of alkalinization, including the segregation of alkaline magmatic liquids.[7]

Bowen's discussion shows how complex are the chemical conditions underlying the differentiation of wholly primary basalt itself; they are not likely to be any simpler if the basaltic liquid has absorbed carbon dioxide, water, or lime from surrounding sediments. However, syntexis of this kind does seem as probable as any other condition yet suggested for the development of melilite basalt, nephelite basalt, basanite, nephelinite, and their close allies.[8] Such liquids are specially

[1] C. N. Fenner, Amer. Jour. Science, vol. 36, 1913, p. 357.

[2] P. Niggli, Die Naturwissenschaften, vol. 45, 1916, p. 686; Trans. Faraday Soc., vol. 20, 1925, p. 430.

[3] S. J. Shand, Trans. Geol. Soc. South Africa, vol. 34, 1931, p. 101.

[4] W. H. Goodchild, Mining Mag., 1918, sep. p. 32.

[5] See R. A. Daly, Bull. Geol. Soc. America, vol. 39, 1928, p. 746.

[6] V. M. Goldschmidt, Videns.-Skrifter, Christiania (Oslo), Kl. I, 1920, No. 10, pp. 119 and 135.

[7] D. Beljankin (Bull. Acad. Sci., U.R.S.S., phys.-math. Cl., 1929, p. 571) believes there is evidence that aluminate of soda is a component of ordinary feldspar.

[8] N. L. Bowen (The Evolution of the Igneous Rocks, Princeton, 1928, p. 270) suggests that nephelinite, with its average of 6.6 per cent soda and 2.5 per cent potash, is the product of mixing basaltic liquid with material of concentrated hornblende. The mixture theoretically precipitates olivine and other early-formed crystals and leaves in the solution the more alkaline part of the hornblendic substance. Since average hornblende, like average hornblendite, has only 1 to 2 per cent of soda or potash, the amount of reacting hornblende necessary is relatively enormous. There is doubt that, at this fairly advanced stage of the crystallization of the assumed original basaltic magma, the lava column could have enough thermal energy to permit so much reaction, especially at deep levels that were

prone to differentiate; hence, while represented among the quickly chilled extrusives, they have exceedingly rare equivalents among plutonic bodies with the characteristically long magmatic life.

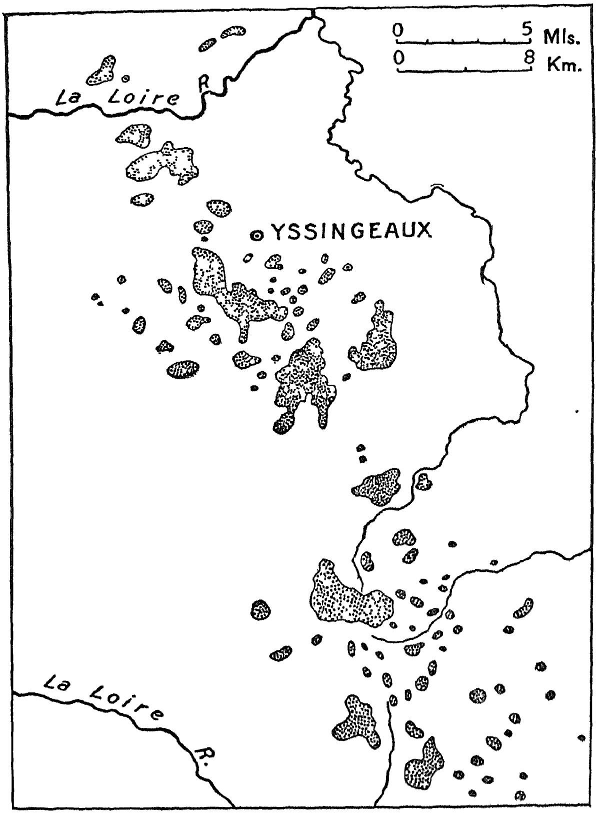

FIG. 168.—Map of phonolites (*stipple*) of the Velay, France. (*After M. Boule, Bull. serv. carte géol. France, No.* 28, 1892, *p.* 147.)

When we reflect upon the wide range among the subalkaline liquids capable of reacting with sediments, upon the wide range of these foreign materials, and upon the flexibility of the differentiating process itself, we can feel no surprise at the great number of rock types in the

already chilled by sunken, older crystals of olivine, etc. A second difficulty with the hypothesis is the general absence of field association between hornblende-bearing rocks and nephelinite. The same two troubles appear also with other "strongly femic alkaline rocks," to which Bowen has applied the hypothesis. A. F. Buddington (Jour. Geol., vol. 35, 1927, p. 240) finds an explanation of the hornblendites of the Alaskan Coast Range by assuming these rocks to have crystallized from olivine-gabbro magma unusually rich in mineralizers—a hypothesis in strong contrast with that of Bowen.

feldspathoidal clans. This last fundamental fact seems endlessly hard to explain on the hypothesis of differentiation from uncontaminated basaltic or other liquid.

Finally, the connection between the duration of magmatic life and chemical changes deserves notice. The nephelite basalts of Germany

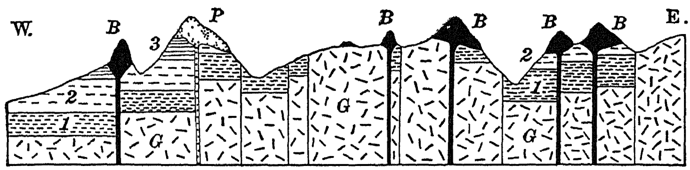

FIG. 169.—East-west section across le Livradois and le Comté, France. *G*, granitic basement; *1*, *2*, *3*, Oligocene; *B*, basalt and tephrite; *P*, phonolite. (*After P. Glangeaud, Bull. serv. carte géol. France, No.* 123, 1909, *p.* 17.)

dominate over the phonolites. The phonolites of France were erupted at many points but always in small volume (Figs. 168, 169). In Italy tephrites and basanites are in greater volume than phonolitic lavas.

TABLE 62.—ALKALINE MAGMAS MODIFIED BY ASSIMILATION OF CARBONATE ROCKS

	1	2	I	II	*a*	*b*	*x*	*y*
SiO_2	70.40	47.20	58.72	52.08	54.85	40 23	71.23	58.55
TiO_2	.13	......	.19	1.38	.69	33	.36	92
Al_2O_3	7.85	10 40	21.40	16.05	18 51	20 33	14.43	15 62
Fe_2O_3	6.98	10.70	.39	3.25	5 81	2 52	1 10	3.02
FeO	2.98	4.10	1.39	5.37	3.38	3 33	.66	2.57
MnO	.13	.....	.....	.....	.08	.10	.03	.17
MgO	.52	1.05	.75	3.67	.18	2.38	.26	1.14
CaO	.26	17.30	1.72	7.74	1.00	11.02	.97	7.34
Na_2O	4.05	1.96	7.10	4.99	11.68	11.10	4.90	5.11
K_2O	4.45	3.27	7.48	3.67	3.65	3.34	6.04	4 16
H_2O	.25	.80	.68	1 26	.....	....	.11	.26
CO_2	.....	2.70	.....	.14	.00	1.26		
P_2O_5	.....	......	.10	.39	.13	3 37	.07	.49
ZrO_2	1.65	1.18						
Total	99.65	100.66	99.92	99.99	99.96	99.31	100.16	99.35

1. Riebeckite granite, Ampasibitika, Madagascar (Lacroix).
2. Garnetiferous syenite, endomorphic phase of 1.
I. Nephelite syenite, Nosy Komba, Madagascar (Lacroix).
II. Nephelitic (essexitic) monzonite, endomorphic phase of I.
a. Foyaite, Sekukuniland (calculated as water free), Shand.
b. Ijolite, endomorphic phase of *a* (calculated as water free).
x. Aegirite-augite granite, Sviatoy Noss, Transbaikalia (Eskola).
y. Sviatonossite (allied to both monzonite and malignite), endomorphic phase of *x*.

These and many other examples show how quick cooling by extrusion checks the natural tendency for salic differentiates to form at or near the top of each magmatic column. On the other hand, the felsic

foyaite dominates among the visible feldspathoidal rocks in plutonic chambers, where the liquids are not so suddenly "fixed," in a chemical sense, by loss of heat.

Some feldspathoidal types cannot be explained by mere gravitational or other kind of differentiation. As might be expected on general grounds, alkali-rich magmas themselves are prone to assimilate carbonate rock, if the temperature conditions are right. That the result is the generation of rocks more or less clearly belonging to what are generally called alkaline suites is shown by studies of endomorphism. Among these are the cases summarized by the analyses of Table 62.[1]

All four of the tabulated examples, like that of Scawt Hill (Table 61, page 503), illustrate the migration of carbon dioxide on a comparatively large scale, and once more the effect of this resurgent gas on other parts of each magma becomes an insistent question. Such hybridism "at a distance," as well as *in situ*, can alone give a great variety of rock types. Differentiation of both kinds of hybrid melts still further complicates the situation. The total change in the primary magma is likely to match the bewildering range of rock types in an important part of the alkaline suite.

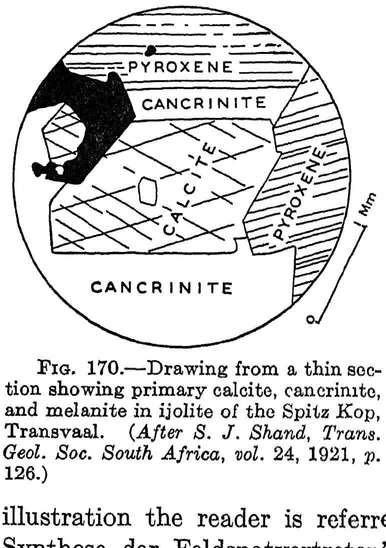

FIG. 170.—Drawing from a thin section showing primary calcite, cancrinite, and melanite in ijolite of the Spitz Kop, Transvaal. (*After S. J. Shand, Trans. Geol. Soc. South Africa, vol.* 24, 1921, *p.* 126.)

Evidence from Mineralogical Composition.—The offered explanation for many feldspathoidal species involves a special mineralogy for them, and one of its strongest merits is that it gives the key to a genetic problem which otherwise seems to have no adequate solution. In illustration the reader is referred to the masterly book "Über die Synthese der Feldspatvertreter" (Leipzig, 1925) by W. Eitel, who there discussed in considerable detail the actual mineralogy of the feldspathoidal rocks.

No reasonable doubt now remains as to the primary nature of the calcite inclosed in many eruptive bodies. A few granites contain it as a rare accessory, but much of the calcite crystallized from igneous melts

[1] Analyses taken from A. Lacroix, Minéralogie de Madagascar, vol. 2, Paris, 1922, pp. 586, 589, 624, 661; and from S. J. Shand, Trans. Geol. Soc. South Africa, vol. 24, 1921, p. 145. *Cf.* P. Eskola, Finska Vetens.-Soc. Förh., vol. 63, 1920–1921, Afd. A, No. 1, p. 79.

has been found in nephelite syenites and their close allies. Well-known examples are described in the memoirs on Alnö, Sweden; the Hastings-Haliburton area, Ontario; the Ice River intrusion, British Columbia; the Spitz Kop, Transvaal (Fig. 170); and Laacher See, Sviatnoy Noss, Coimbatore, Koraput, Loch Borolan, Botogolsky-Golez, Zarafschan, Kuolajarvi, and Seiland. Brogger's monograph on the Fen region (pages 337–347) summarizes most of these cases. He doubts (page 336) an origin of the primary calcite of granite in "ordinary differentiation" without a previous absorption of foreign carbonate in the magma. If calcite-bearing granites were produced by pure differentiation, according to the views of Bowen and Smyth, then one may well ask with Brögger why such rocks are so rare.[1]

Cancrinite was first named at Miask (Urals), where, in company with scapolite and corundum, it is a primary (late-magmatic) constituent of nephelite syenite cutting thick limestone. According to Thugutt, its complex formula contains five molecules of $CaCO_3$, one of Na_2CO_3 and, also suggestively, three of sodium aluminate. Preobrajensky found the nephelite syenite of Upper Zarafshan (Turkestan) to contain cancrinite, idiomorphic calcite, titanite, and sodalite; the cancrinite forms strips parallel to the contact with limestone, intruded by the syenite. The original litchfieldite, furnishing museum specimens of cancrinite and sodalite, cuts crystalline schists with which calcareous rocks are interbedded. Streckeisen shows cancrinite to be well distributed through the nephelite syenite, tinguaite, and alkali-syenite at the classic locality of Ditro, Roumania, where again limestones appear among the country rocks. Is it possible to ignore these and many other cases when the attempt is made to develop a workable theory of the feldspathoidal rocks?[2]

The local excess of lime in strongly alkaline magmas or in the rocks that are manifestly syngenetic with them is suggested also by the

[1] Compare K. H. Scheumann's able discussion of the problem of magmatic calcite in the Polzen rocks (Centralb. f. Mineralogie, etc., 1922, pp. 495 *ff.*), for which W. Eitel (Über die Synthese der Feldspatvertreter, 1925, p. 160) *ohne Zweifel* adopts the syntectic hypothesis. Among the most recent discoveries of primary calcite in andesites and basalt are those reported by C. Burri and H. Huber (Schweiz. Min. Petr. Mitt., vol. 12, 1932, pp. 307–337).

[2] S. J. Thugutt, Neues Jahrb. f. Mineralogie, etc., 1911, vol. 1, p. 45. J. A. Preobrajensky, Annales Inst. Polytech. Pierre le Grand, St. Petersburg, vol. 15, 1911, p. 203. R. A. Daly, Field Relations of Litchfieldite and Soda-syenites of Litchfield, Maine, Bull. Geol. Soc. America, vol. 29, 1918, p. 463. A. Streckeisen, Neues Jahrb. f. Mineralogie, etc., B.B. 1931, A, p. 623. See the discussion of cancrinite rocks by P. Quensel, Bull. Geol. Inst. Upsala, vol. 12, 1914, p. 169. T. Barth (Norske Videns.-Akad., Kl. I, 1927, No. 8, pp. 13, 81) found cancrinite as a synantetic mineral between the plagioclase of olivine anorthosite and included grains of calcite.

formation of melilite, scapolite, vesuvianite, wollastonite, diopside, lime-garnets, and perhaps anorthoclase itself.

Several cases have been reported where melilite seems to be the product of assimilation of carbonate rock. Such is Becker's explanation of the melilite in the basalt of the Wartenberg, Germany. Starabba concluded that the 1883, 1886, 1892, and 1910 lavas of Etna absorbed limestone, with the crystallization of melilite as a result. Tilley and Harwood attribute the melilite of the Scawt Hill rocks to reaction of doleritic liquid with limestone. These authors believe that even types wherein melilite is the preponderating mineral are "extreme hybrids between magmatic solutions and limestone" and are not metasomatic replacements.[1]

Bowen, basing his argument on artificial melts, regards the melilite of igneous rocks as in general due to the reaction of an alkaline (nephelite-rich) liquid with crystallized augite, producing "monticellite and melilite, acting, as it were, as a desilicating agent." He suggests also that an analcite-rich liquid is produced by the reaction and adds:

> In deep-seated rocks the reaction between nephelite and pyroxene to produce analcite and melilite is reversed. It is probable that some melilite is produced by the addition of lime to ordinary basalts, but when so formed one would expect it to be found in deep-seated rocks as commonly as in effusive and dike rocks. The fact that melilite is practically absent from deep-seated rocks suggests the dominance of the other mode of production, namely, interaction of nephelite and pyroxene which requires the rapid cooling accompanying eruption in order to prevent its reversal at lower temperatures.[2]

But cooling must have been slow at Scawt Hill, and there are not wanting instances where petrologists have found melilite in plutonic rocks. Thus Brögger reports this mineral in the biotite-nephelite type turjaite, which corresponds nearly to the effusive leucite-bearing melilite-nephelinite, and explains the melilite of turjaite as a crystallization from a limestone syntectic. So also Erdmannsdörffer and Nieland conclude that the melilite of the Tasmanian fasinite, another granular species of rock, was not the result of the Bowen reaction and appear to prefer an origin in syntexis of magma with carbonate rock.[3]

Again, the Bowen reaction does not seem to be relevant in a not uncommon case represented by melilite basalt, where

[1] E. Becker, Zeit. deut. geol. Gesell., vol. 59, 1907, pp. 244, 401. Stella Starabba, Red. R. Accad. Lincei, vol. 19, 1910, p. 755. C. E. Tilley and H. F. Harwood, Miner. Mag., vol. 22, 1931, p. 457.

[2] N. L. Bowen, Jour. Washington Acad. Sciences, vol. 13, 1923, p. 2.

[3] W. C. Brögger, Das Fengebiet in Telemarken, etc., Christiania (Oslo), 1921, pp. 380–382. O. H. Erdmannsdörffer and H. Nieland, Fennia, vol. 50, No. 4, 1928, p. 10.

melilite is accompanied by wollastonite, hauynite, garnet, and perovskite.

It seems probable, therefore, that the presence of melilite in rocks of an alkaline series and their congeners is commonly an indication of syntexis of the kind suggested.

Primary scapolite is associated with primary calcite in the nephelite syenites of the Hastings-Haliburton district, Ontario (Fig. 171). The tinguaite of Spotted Fawn Creek, Yukon, contains essential leucite, with scapolite in its groundmass.[1] Calkins explains the scapolite of pyroxene aplites near Philipsburg, Montana, by the absorption of

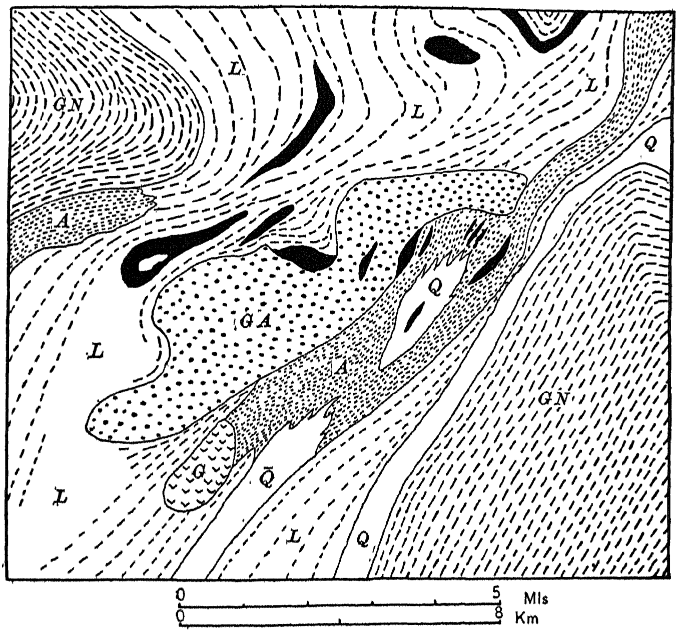

FIG. 171.—Map of the Glamorgan gabbro, Ontario. *L*, Grenville limestone; *A*, amphibolite; *Q*, quartzite and paragneiss; *GN*, intrusive granite-gneiss; *G*, intrusive granite; *solid black*, nephelite syenite; *GA*, gabbro. Strike lines indicated in *GN*, *A*, and *L*. (*After F. D. Adams and A. E. Barlow, Memoir* 6, *Geol. Survey Canada*, 1910.)

limestone in siliceous alkaline magma resembling that of normal aplite.[2] Barth describes the occurrence of carbonate-marialite and carbonate-meionite in the canadite dikes of Seiland, both of these scapolites being of magmatic origin, though dependent for their formation upon preliminary absorption of carbon dioxide from limestone.[3] Similarly

[1] C. W. Knight, Amer. Jour. Science, vol. 21, 1906, p. 286.

[2] F. C. Calkins, Prof. Paper 78, U.S. Geol. Survey, 1913, p. 126.

[3] T. Barth, Norske Videns.-Akad., Oslo, math.-nat. Kl. 1927, No. 8, pp. 82–91, 116. See Barth's general discussion, with references.

Eskola accounts for scapolite, primary calcite, epidote, and graphite in sviatonossite.[1]

Quensel tentatively attributes the vesuvianite, a truly magmatic constituent, of the nepheline-bearing rocks of Almunge, to the assimilation of limestone in depth.[2] Barth holds a similar opinion in connection with the vesuvianite of the Seiland canadite, just mentioned.

That the diopside itself may be largely of syntectic origin is suggested by the analogy with rock or magma of the subalkaline kind. For example, Umpleby ascribed the diopsidization of Idaho granite to absorption of limestone, the lime replacing soda. Eckermann believes that some of the diopside in the eulysite of Mansjo Mountain was formed from a syntectic with limestone, to which mixing he also attributes the abundant apatite in certain dikes of the region. Watson, like Eskola, found ordinary granite-pegmatite to have absorbed limestone, thus becoming notably diopsidic. Osborne describes hybrid diopside rocks merging externally into skarn and internally into quartz monzonite, which represents the original reacting magma.[3]

According to Rittmann, the diopside-hedenbergite series of pyroxenes in the more mafic Ischian eruptives were precipitated in special amounts because of the assimilation of limestone at depth. He favors a similar explanation for much of the augite in the Vesuvian lavas.[4]

The lime-bearing titanite and perovskite are also suspiciously abundant in many species of alkaline rocks. The more felsic species, foyaite, phonolite, etc., generally tend to be correspondingly poor in ilmenite or titaniferous magnetite. Both facts are explicable on the view that these differentiates have been derived from a limestone syntectic. Some ferrous iron should enter the augite and other cafemic

[1] P. Eskola, Finska Vetens.-soc. Förh., vol. 63, 1920–1921, Afd. A, No. 1, p. 95. For experiments bearing upon the genesis of scapolite, see W. Eitel, Tschermaks Min. und Petr. Mitt., vol. 38, 1925, p. 1.

[2] P. Quensel, Bull. Geol. Inst. Upsala, vol. 12, 1914, p. 175.

[3] J. B. Umpleby, Prof. Paper 97, U.S. Geol. Survey, 1917, p. 60. H. von Eckermann, Geol. Fören. Förh. Stockholm, 1922, pp. 260, 337. E. H. Watson, Econ. Geol., vol. 24, 1929, p. 611. P. Eskola, Finska Vetens.-Soc. Förh., vol. 63, Afd. A, No. 1, 1920–1921, p. 37 ("The diopside-pegmatite is really confined to the limestone and to the vicinity of the limestone masses"). G. D. Osborne, Geol. Mag., vol. 68, 1931, p. 311. Compare the Palabora case described by S. J. Shand (Trans. Geol. Soc. South Africa, vol. 34, 1932, pp. 85 and *xlviii*) and A. L. du Toit (*ibid.*, p. 107). Shand concludes that the Palabora pyroxenites examined by him are of magmatic origin and represent desilication of granitic magma, while accepting the possibility that du Toit may be right in attributing some of the pyroxenite to contact metamorphism of the limestone by the intrusive granite.

[4] A. Rittmann, Zeit. f. Vulkanologie, Erg. Heft 6, 1930, p. 249; Die Naturwissenschaften, vol. 20, 1932, p. 305.

molecules formed by inoculation with foreign lime. Titanic oxide is thus free to combine with lime, forming stable compounds. These seem to be specially associated with the volatiles and, as in the Turkestan intrusives above noted, may be driven into the surrounding limestone. In fact, there is good field evidence that titanite tends to accompany the alkalies as these are magmatically concentrated. Benson found the soda-rich rocks of Southern Australia and of Eastern Australia to be characteristically rich in titanic oxide. Pacàk attributes the titanite in Moravian teschenite to the assimilation of calcareous rocks. Titanite, along with primary calcite and the lime-rich microlite, melanite, and apatite is remarkably abundant in the alkaline rocks of the Fen region, where these igneous types are spectacularly associated with carbonatic types.[1]

It seems natural to assume that free carbon may be expected in strongly alkaline rocks if these are products of syntexis with carbonate rocks and if the absorbed sediment was carbonaceous. Graphite has, in fact, been described among the magmatic crystallizations in the nephelite syenites of India and Ontario. Laitakari, like Jaczewski twenty-five years before, concluded that the Alibert graphite of Siberia resulted from the process described.[2]

In the last chapter we saw some reason to explain analcitic rocks by the absorption of foreign water. Petrographers are increasingly of opinion that analcite is primary in rocks like analcite basalt, crinanite, analcite syenite, teschenite, monchiquite, blairmorite, and

[1] W. N. Benson, Trans. Roy. Soc. South Australia, vol. 33, 1909, p. 138., O. Pacák, Bull. internat. Acad. Sci. Bohême, 1926, sep. pp. 16, 69. W. C. Brögger. Das Fengebiet in Telemarken, Norwegen, Oslo, 1921, pp. 54–56, 113, 153, 217, etc, Compare W. R. Browne (Trans. Roy. Soc. South Australia, vol. 44, 1920, p. 55) who notes that titania accompanies soda in volatile transfer from syenitic magma to the country rocks; also E. Kaiser (Die Diamantenwüste Sudwest-Afrikas, Berlin, 1926, p. 265).

[2] A. Laitakari, Geotekn. Medd. Geol. Kommissionen, Helsinki, 1925, p. 60. L. Jaczewski, Explorations le long du chemin de fer Sibérien, livre 11, 1899, p. 19 [abstract in Neues Jahrb. f. Mineralogie, etc., 1901 (2), p. 74]. This Siberian nephelite syenite is associated with hornblende granite, biotite granite, and syenite—all four plutonics cutting gneiss, mica schist, metargillite, and thick limestone carrying abundant graphite.

P. Eskola (Öfversikt Finska Vetens.-Soc. Förh., vol. 63, Abt. A, 1920–1921, p. 38) found the granite pegmatites of Sviatoy Noss, Transbaikalia, to contain much graphite only where they cut the graphitic limestone. A similar relation characterizes Finnish pegmatites, according to Laitakari.

A. K. Banerji (Rec. Geol. Survey India, vol. 66, 1932, pp. 22, 94) describes a granite-pegmatite dike cutting limestone, the endomorphic phase along the wall of the dike containing graphite as well as scapolite, diopside, and calcite. He notes also (p. 95) the carbonate-desilication of albite to nephelite in a ruby-bearing dike in Burma; diopside is another product of the reaction.

shackanite, though any of these types may also display the results of later "hydrothermal analcitization."[1] The concentration of analcite in any of the types listed or in the highly mafic species, such as the teschenitic peridotite and picrite of the Inchcolm sill, is not easily explicable on any theory that assumes the water involved to be purely juvenile in origin. Nor can those species represent liquids residual in the crystallization of basalt at the stage required to account for the actual high percentages of water present. On the other hand, resurgent water can enter a magma at any stage of its crystallization.[2]

Phonolitic magma, like the trachytic, has been generated in narrow volcanic pipes run through basaltic piles, where the conditions favor the rise and concentration of both juvenile and resurgent water and carbon dioxide, as well as the selective solution of basaltic rock. Accordingly we encounter another possibility. Lacroix regards analcite as a combination of nephelite, albite, and water:

$$NaAlSiO_4 + NaAlSi_3O_8 + 2H_2O = 2NaAl(SiO_3)_2.H_2O.$$

Thus he assumes analcitic tephrites and analcitic basanites to result when, on account of abundant water, analcite instead of nephelite crystallizes from the corresponding femic melts. If residual liquid containing the analcite molecule rises to the top of a volcanic pipe, much water escapes to the air. There, with crystallization, albite and nephelite instead of analcite will form. Were the weakly nephelitic phonolites of Saint Helena and other dominantly basaltic cones so produced? Favoring this idea is the remarkably small development of bubble vesicles and amygdules in those rocks. The deeper rocks of each cone, whether submarine or subaerial, doubtless carry connate water liable to resurgency; hence there is no difficulty in crediting the special generation of the analcite molecule.[3]

Differentiation of Feldspathoidal Rocks in Place

The active control of gravity seems as manifest as it is with bodies belonging to other clans. In Chapter XIV we noted the gravitative

[1] As in the case of calcite, cancrinite, albite, or quartz, there is no sharp dividing line between the magmatic and hydrothermal formation of analcite.

Among recent memoirs dealing with rocks bearing primary analcite are the following: G. W. Tyrrell, Geol. Mag., vol. 60, 1923, p. 249, with references; O. Pacák (Moravian teschenites), Bull. internat. Acad. Sci. Bohême, 1926, p. 1; J. D. Mackenzie, Museum Bull. 4, Geol. Survey Canada, 1914; R. A. Daly (shackanite), Mem. 38, *ibid.*, 1912, p. 411. A. Harker, Pres. Add. British Assoc. Adv. Science, Portsmouth meeting, 1911, p. 9. R. Campbell, T. C. Day, and A. G. Stenhouse, Trans. Edinburgh Geol. Soc., vol. 12, 1932, p. 342 (Braefoot sill).

[2] Compare Fig. 195 of "Igneous Rocks and Their Origin" with accompanying text giving reference to the paper by R. Campbell and A. G. Stenhouse on absorption of sediments by the picritic sill of Inchcolm Island, Scotland.

[3] *Cf.* S. J. Shand, Quart. Jour. Geol. Soc. London, vol. 89. 1933, p. 11.

separation of nephelite syenite and sodalite syenite from shonkinite in the Shonkin Sag and Square Butte laccoliths, the initial liquid being a leucite basalt. After detailed work among the Scottish sills, Tyrrell explains on the same principle the kylite-picrite association at Benbeoch, the picrite-teschenite association at Castle Craigs, and the analcite syenite and crinanite phases of the Howford Bridge sill. So it is, according to Walker, with the separation of analcite syenite, teschenite, and dolerite in the Shiant Isles sill (see page 474). Lowe found the Lurcombe sill, Devonshire, to have a camptonitic layer at the roof, teschenite in the middle, and an augitic phase at the bottom.[1]

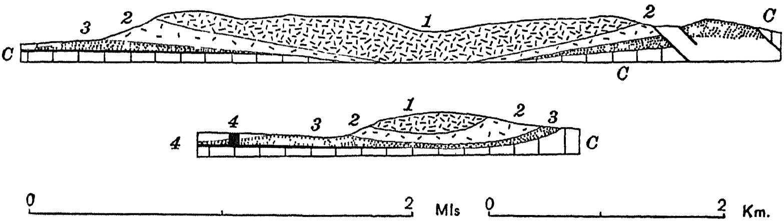

FIG. 172.—Sections of the Cnoc-na-Sroine (Loch Borolan) laccolith, Scotland. *C*, Cambrian, *1*, quartz syenites; *2*, transition rocks; *3*, melanite-nephelite syenites, augite-nephelite syenites, etc.; *4*, hypothetical ultrabasic layer. The upper section runs northwest-southeast; the lower at right angles. (*After S. J. Shand, Trans. Edinburgh Geol. Soc., vol.* 9, 1910, *p.* 379.)

The Grosspriesen laccolith of the Bohemian Mittelgebirge exhibits sodalite syenite in outcrop, the Tertiary roof still partly extant. The situation of the syenite is thus suggestively like that of the sodalite syenite at Square Butte.[2]

The Borolan laccolith at Cnoc-na-Sroine, Scotland, measures 4 miles by 2.5 miles in outcrop, with a probable original thickness of about 0.25 mile. The roof has been eroded away. Shand's section is reproduced in Fig. 172. The intrusion is stratified in the following order:

Phase	Stratification	Approximate specific gravity
	Erosion surface	
1	Quartz syenites	2 625–2.635
2	Transition zone of quartz-free syenite	2.65
3	Melanite-nephelite syenite and ledmorite	2.74–2.78
	Base concealed	

[1] H. J. Lowe, Geol. Mag., vol. 5, 1908, p. 344. G. W. Tyrrell, Geol. Mag., vol. 9, 1912, pp. 73, 123; Trans. Geol. Soc. Glasgow, vol. 13, 1909, p. 309. H. J. Lowe, Geol. Mag., vol. 5, 1908, p. 344.

[2] J. E. Hibsch, Tschermaks Min. u. Petr. Mitt., vol. 21, 1902, pp. 157, 465.

Shand favors the hypothesis that the concealed floor phase is composed of melanite pyroxenite, like that observed as locally intrusive into phase 3.[1]

The advanced character of this clearly gravitative separation, in a sheet of rather moderate thickness, is one more illustration of the decided fluidity of alkaline magmas, however viscous some artificial alkali-rich melts may be. This case throws light on the syngenesis of

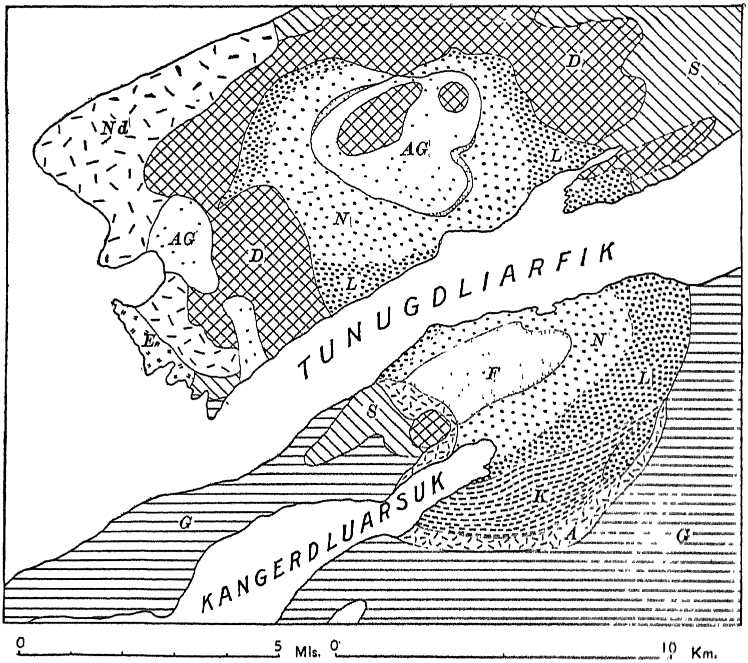

FIG. 173.—Map of the Ilimausak intrusion, Greenland. *G*, granite; *S*, sandstone; *D*, diabase and porphyries; *E*, essexite; *A*, augite syenite; *L*, lujavrite; *K*, kakortokite; *N*, naujaite; *F*, sodalite foyaite; *Nd*, nordmarkite; *AG*, arfvedsonite granite. (*After N. V. Ussing, Medd. om Grönland, vol.* 38, 1911, *plate* 3.)

soda granites, nordmarkites, foyaites, etc., in such rock assemblages as those of the Christiania region and Predazzo.

The able memoir by Ussing, on the Julianehaab district of Greenland, describes a remarkable group of alkaline rocks which have crystallized from magmas differentiated, at least in part, under the dominating influence of gravity.[2] The sodalite foyaite, "naujaite," lujavrite, and "kakortokite" of the Ilimausak intrusion—all related to foyaite—were so interpreted by Ussing (Fig. 173). These and the other

[1] S. J. Shand, Trans. Edinburgh Geol. Soc., vol. 9, 1910, p. 376.

[2] N. V. Ussing, Geology of the Country around Julianehaab, Greenland, Copenhagen, 1911, pp. 318, 348, etc.

rocks of the mass occur as successive nearly horizontal sheets, named in order, from above downward:

	Thickness, meters	Specific gravity
Arfvedsonite granite	150–400	2 66–2 72
Quartz syenite	0–20	(?)
Pulaskite	10–30	2.72
Foyaite	0–10 (?)	2.67
Sodalite foyaite	2–150 (average, 100)	2.65
Naujaite	200–600 (average, 300)	2.53
Lujavrites and kakortokites	600+	2 75–3 12

The naujaitic layer (highly sodalitic) is explained by an upward transfer of the sodalite molecule from the deeper part of the mass; the more ferrous and less aluminous lujavrite-kakortokite magma, as the residual liquor left after the gravitative removal of the sodalite. Ussing considered it likely that this substance was transferred in the form of solid crystals. The sodalite foyaite above the naujaite represents nearly the chemical composition of the magma before this differentiation took place. Ussing did not attribute the foyaitic phase to the relatively quick chilling of the original magma near the roof of the intrusion, but gave a hypothetical explanation detailed on page 354 of his memoir. That hypothesis, involving the rise of magmatic gases, also implies gravitative control.

Ussing explained the arfvedsonite-granite phase as probably due to the assimilation of the sandstone intruded by the foyaitic magma—assimilation in place. Stoped-down blocks of sandstone are surrounded by thick shells of this granite merging outward into alkaline syenite. The syenite in its turn merges into the nephelite-bearing rocks. In this connection the discovery of a layer of augite syenite at the *lower* contact of, and below the denser lujavrites of, the neighboring Igaliko intrusion is significant.[1] Nevertheless, it is possible that the granitic magma was largely differentiated from the sandstone syntectic and solidified *before* the main foyaitic magma was differentiated. The granitic magma was clearly less dense than the undifferentiated foyaite, so that this initial separation was controlled by gravity. Afterwards the deeper-lying, still-fluid foyaite separated into the strongly contrasted naujaite and lujavrite. The upward transfer of alkali is shown by the abundance of sodalite in the overlying naujaite. Allan has observed a similar segregation of sodalitic rock near the roof of the alkaline intrusion at Ice River, British Columbia.[2]

[1] See sections in Ussing's memoir on pp. 252, 253, and also those on pp. 38, 39, 42, and 61.

[2] J. A. Allan, Mem. 55, Geol. Survey Canada, 1914, p. 125.

In passing, it may be noted that the Ilimausak and still larger Igaliko "batholiths" often have concordant or roughly concordant relations to the invaded sandstone. The contacts of the Ilimausak intrusion are like those at the roof of a chonolith or an irregular, partly crosscutting laccolith. The sections on pages 252 and 253 of Ussing's book, when compared with the map in Plate IV, strongly suggest that the Igaliko body is an irregular laccolith or lopolith with base exposed.

The memoir further describes an unusually perfect and full illustration of primary banding. The kakortokites of the lowest visible phase are arranged in layers of black, white, and red colors, corresponding to great differences in specific gravity and mineral composition (Fig. 174).

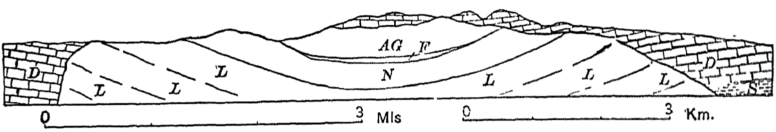

FIG. 174.—Section of the Ilimausak intrusion from west-southwest to east-northeast. (Same reference as for Fig. 173.)

The peculiar kind of stratification characterizing the kakortokitic complex will appear from the following list of a number of consecutive sheets:

Kakortokite	Thickness, meters	Specific gravity
Black	*ca* 2–3	*ca.* 3.12
White	*ca.* 6–9	*ca.* 2.76
Red	*ca.* 1–2	*ca.* 2.85
Black	*ca.* 2–3	*ca.* 3.12
White	*ca.* 6–9	*ca.* 2.76
Red	*ca.* 1–2	*ca.* 2.85
Black	*ca.* 2–3	*ca.* 3.12

The succession as given in this table continues through a total thickness of about 400 meters, the number of individual sheets amounting to more than a hundred, while the number of repetitions of color sets is about forty. It is worth mentioning that the red sheets in many places are badly developed or even wanting, but even in such cases the lowermost portions of the white sheets or the uppermost portions of the black ones are relatively rich in eudialyte . . .

That gravitative separation is able to account for the differentiation will appear from the following consideration. The black kakortokite sheets (sp. gr. 3.12) are characterized by the abundance of arfvedsonite (sp. gr. 3.4); the red sheets (2.85) which overlie the black ones abound in eudialyte (2.9); and the white rock (2.76) which covers the red sheets has alkali felspar as its dominant mineral (2.6). The arrangement thus agrees with what should be expected if it were due to gravitation . . .

For the banded kakortokite of the Ilimausak complex the simplest supposition is perhaps that the recurrent layers have originated in consequence of

repeated variations in pressure. Each reduction in the pressure may have caused the dissociation of a certain quantity of volatile matter from the magma, and this process in its turn may have caused the crystallization of a certain quantity of the magma.[1]

The variation of pressure is supposed to be due to volcanic outbursts from the magma chamber.

Similar primary banding is seen in the great foyaitic laccolith of the Kola Peninsula, in the malignite-nephelite syenite body of Kruger Mountain in the Cascade range (Canada-United States boundary line), and in many other plutonic alkaline masses.

Field Association with the Gabbro Clan

The general theory predicts two modes of this association. The connection may be direct, where members of the gabbro clan are clearly syngenetic with feldspathoidal rocks; or indirect, where the latter are syngenetic with differentiates of basalt or of basaltic syntectics.

The *direct* relation may be in the form of (*a*) transitions or (*b*) adjacent separate eruptions accomplished during the same petrogenetic cycle.

Transitions from feldspathoidal rock to typical basaltic material are not common, though a growing number of cases are reported where analcitic phases actually pass into diabasic or allied rock devoid of any feldspathoid. That transitions of this kind are rare is a fact expected on the hypothesis of syntexis. The absorption of carbonate has a strong chemical effect on primary liquid, which therefore tends specially to differentiate. Hence we should not expect gradual passage from a feldspathoidal phase to normal basalt, diabase, or gabbro to be as widely exemplified as the transitions between these mafic types and the quartz-bearing clans, when derived from siliceous syntectics.

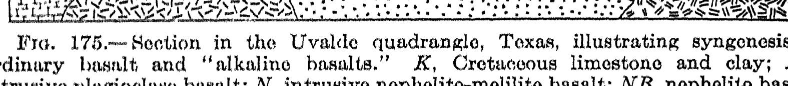

FIG. 175.—Section in the Uvalde quadrangle, Texas, illustrating syngenesis of ordinary basalt and "alkaline basalts." *K*, Cretaceous limestone and clay; *PB*, intrusive plagioclase basalt; *N*, intrusive nephelite-melilite basalt; *NB*, nephelite basalt. Horizontal scale, 1:95,000; vertical scale, 1:12,000. (*After Uvalde folio, U. S. Geol. Survey*, 1900.)

Close association in the form of separate syngenetic bodies is familiar to unprejudiced observers who have worked during the last two decades. Figure 175 shows the intimacy between the plagioclase basalt and nephelite-melilite basalt of a local area in the Uvalde

[1] N. V. Ussing, *op. cit.*, p. 356.

Mountains, Texas. Nephelite appears in some of the historic flows of Etna, though apparently not in those of prehistoric time, when the lavas were dominantly basaltic and andesitic.[1] The Roccamonfina cone carries both leucitic rocks and common basalts (Fig. 176).[2] Many associations of basaltic and feldspathoidal or alkali-rich types are known in Hawaii, Samoa, Tahiti, Possession Island, New Zealand (Dunedin, Figs. 177, 178), Juan Fernandez Islands, Sao Thomé,

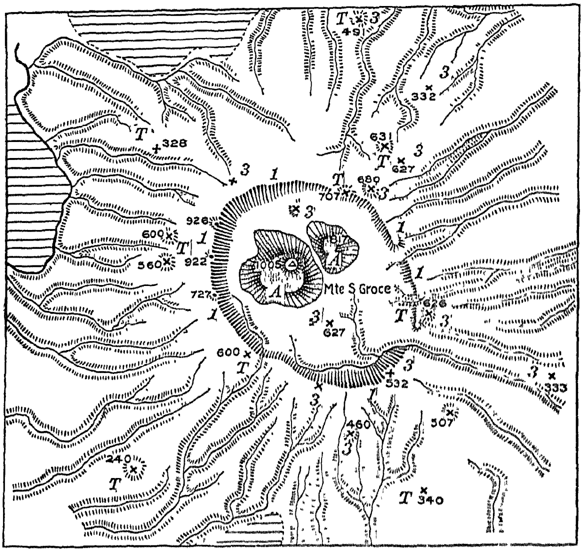

Fig. 176.—Map of Roccamonfina volcano, Italy, illustrating intimate association of basalt, andesite, and alkaline types. *Cross-lining*, Mesozoic and Tertiary basement rocks; *1*, leucitites and leucite tephrites of the first eruptive period; *A*, augite andesites of the second eruptive period; *T*, trachytes and leucitophyres of the second eruptive period; *3*, basalts of the third eruptive period. Lateral eruptions shown by crosses; where also altitudes in meters. Scale, 1:215,000.

Réunion, Madagascar (Fig. 179),[3] Canary Islands, Cape Verde Islands (see J. B. Bebiano, 1927), Azores, Madeira, Pantelleria, etc. The assemblages of lavas in Germany have meaning. In the Lower Rhine region, plagioclase basalts (olivine-bearing and olivine-free), augite andesite, hornblende andesite, nephelite basalt, trachyte, and phonolite have been erupted since the Miocene. In the Upper Rhine region, feldspar basalts, melilite basalt, nephelite basalt, leucite-nephelite basalt, tephrite, limburgite, and phonolite date from the same period. Very similar types were extruded in the Lower Rhine region during

[1] H. S. Washington, Amer. Jour. Science, vol. 12, 1926, p. 404.

[2] W. Kranz, Petermann's Mitt., vol. 58, 1912, p. 131, Pl. 26. *Cf.* H. Johnston-Lavis, The South Italian Volcanoes, Naples, 1891, p. 26.

[3] A later map of northern Madagascar, but on a smaller scale, will be found in vol. 3 of A. Lacroix, Minéralogie de Madagascar, Paris, 1923.

the Quaternary.[1] The assemblages at the Mont Dore, Velay, Cantal (Fig. 180), Limagne, and le Livradois volcanic centers of France, and those in the Bohemian Mittelgebirge tell the same story. In each district, alkali-rich rocks and subalkaline rocks are not only close

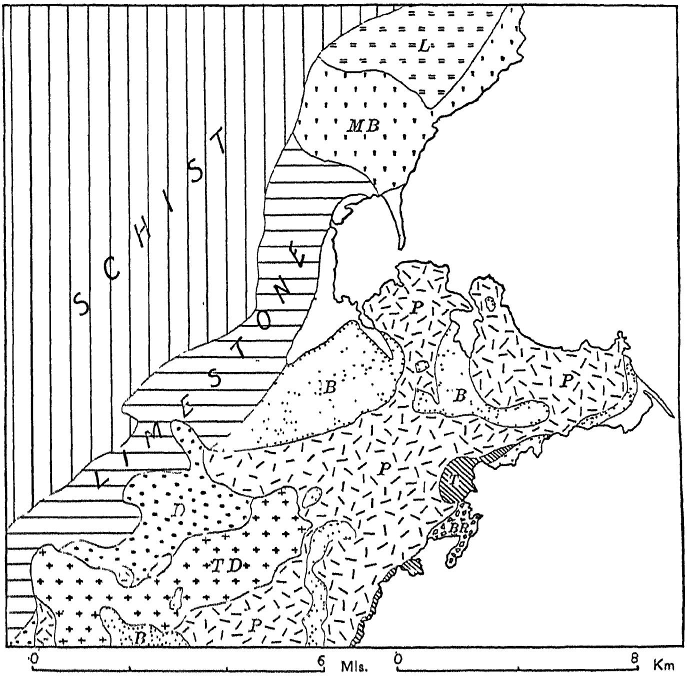

FIG. 177.—Map of part of the Dunedin district, New Zealand, illustrating the close association of alkaline and subalkaline types. *T*, trachyte; *BR*, breccia; *P*, phonolite, *TD*, trachydolerite; *B*, basalt; *D*, dolerite; *solid black*, nephelite basanite; *L*, leucitophyre; *MB*, melilite basanite; *blank*, sand and alluvium. (*After P. Marshall, Quart. Jour. Geol. Soc. London, vol.* 62, 1906, *plate* 36.)

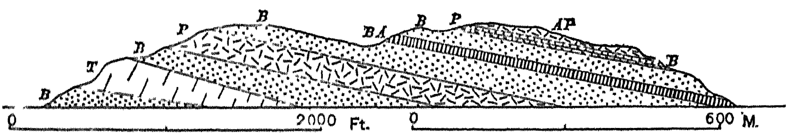

FIG. 178.—Section at North Otago Head in the area of Fig. 177. *B*, basalt; *T*, trachyte; *BA*, basanite; *P*, phonolite; *AP*, andesitic phonolite. (Same reference as for Fig. 177.)

together in space; their eruptions fall, respectively, within the limits of a *short* geological period.

Such repeated close associations, in both space and time, make it incredible that each set of alkali-rich lavas has an origin independent of that to be assigned to the accompanying basalts. Along with

[1] R. Lepsius, Geologie von Deutschland, Teil 2, Leipzig, 1887–1910.

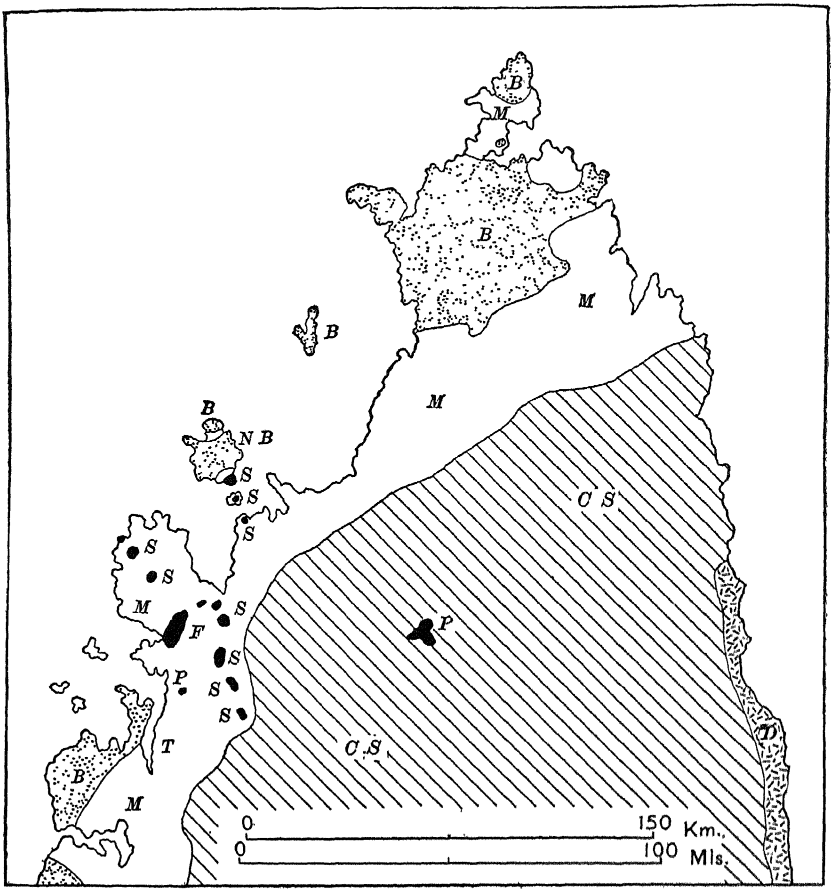

FIG. 179.—Map of northern Madagascar. *CS*, crystalline schists and marbles; *M*, Jurassic and Cretaceous, largely limestone; *S*, syenite; *F*, foyaite; *P*, phonolite; *T*, trachyte; *NB*, nephelite basalt; *B*, basalt, chiefly olivine-bearing; *D*, dolerite. (*After R. Baron, Quart. Jour. Geol. Soc. London, vol.* 51, 1895, *and P. Lemoine, Études géologiques dans le nord de Madagascar, Paris*, 1906.)

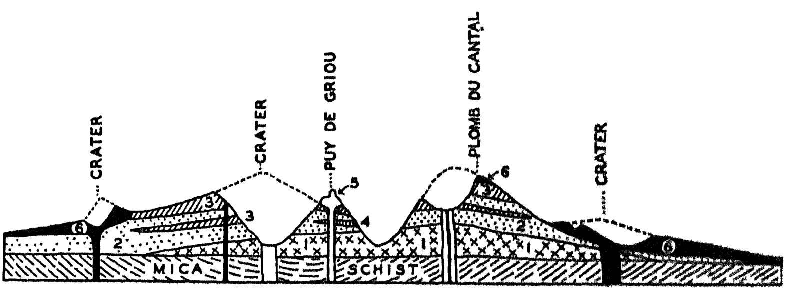

FIG. 180.—Section in arc across the Cantal, France (about 50 kilometers long). *1*, Miocene trachy-phonolites; *2*, andesitic pyroclastics; *3*, andesite; *4*, porphyritic basalt; *5*, phonolite; *6*, Pliocene basalt. (*After B. de Black and P. Marty, Bull. soc. géol. France*, 1921, *p.* 241.)

Washington and others, Lacroix has accumulated facts gained in both oceanic and continental regions, all going to show that there is no systematic geographical separation of subalkaline and feldspathoidal species.[1]

The *indirect* association is not less striking. Short-lived local eruptivity formed the breccia near Blairmore, Alberta. The breccia fragments include augite trachyte, analcite trachyte, tinguaite, and also typical andesite.[2] In Java leucitic, tephritic, and nephelinitic lavas appear among the dominant andesitic eruptives. Lacroix found andesites, basaltic types, and leucitites in the same breccia series near Trebizond.[3]

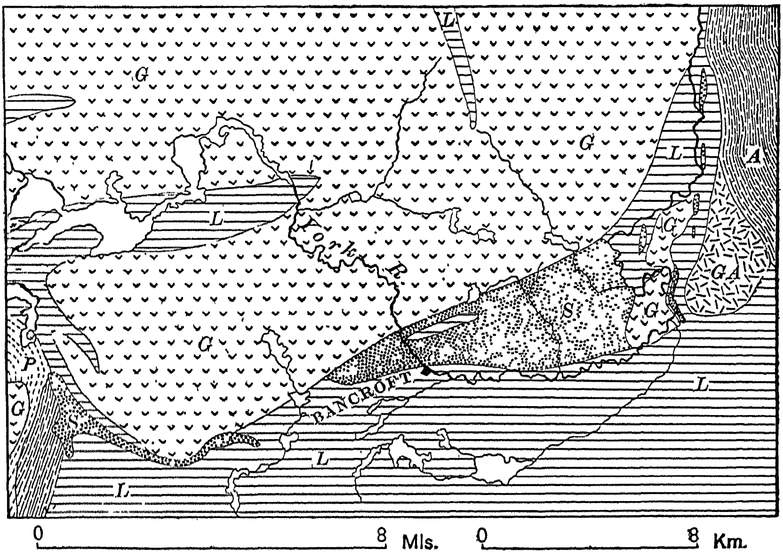

FIG. 181.—Map of the Bancroft district, Ontario. *P*, paragneiss; *L*, Grenville limestone, etc.; *A*, amphibolite; *GA*, gabbro; *G*, granite and orthogneiss; *S*, nephelite syenite. (*After F. D. Adams and A. E. Barlow, Memoir* 6, *Geol. Survey Canada*, 1910.)

The close field association of calc-alkaline and alkaline types is admirably illustrated in eastern Africa (e.g., in Somaliland, Abyssinia, Kordofan, and the islands of Lake Rudolf; along the Uganda Railway and in the Kavirondo country; in the neighbourhood of Mount Meru and Kilima Njaro; along the Singwe River, and in Mozambique). In every case where the relations have been established, it is found that the eruption of the calc-alkaline series pre-

[1] A. Lacroix (Compte Rendu Acad. Sci. Paris, vol. 155, 1912, sep. p. 6) mentions a dike in the Island of Réunion, which furnishes a good analogy. This dike represents "incomplete differentiation," one phase being typical gabbro and another a "monzonitic" rock with nearly 11 per cent alkalies.

[2] J. D. Mackenzie, Museum Bull. 4, Geol. Survey Canada, 1914.

[3] A. Lacroix, Bull. soc. géol. France, vol. 19, 1891, p. 732.

ceded that of the alkaline series, and that the andesites belonging to the former series are associated with basalts heavily charged with an excess of silica. On the other hand, the basalts associated with the alkaline lavas are undersaturated in silica.[1]

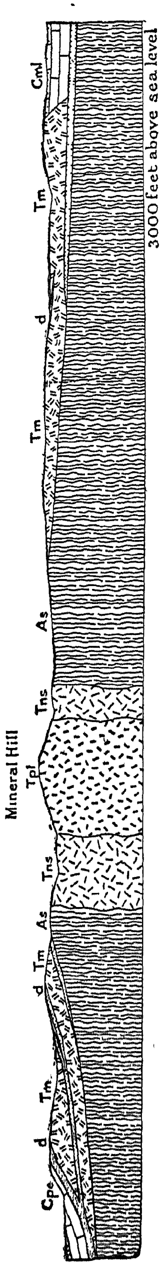

FIG. 182.—Section through the Nigger Hill laccolith, Wyoming, illustrating intimate relations among members of the syenite and "alkaline" clans. *As*, mica schist; *d*, Cambrian; *Cpe* and *Cml*, Carboniferous; *Tm*, monzonite and syenite porphyries; *Tns*, nephelite syenite; *Tpl*, pseudoleucite porphyry. Horizontal and vertical scales, 1:73,000. (*After Sundance folio, U. S. Geol. Survey*, 1905.)

The same type of association appears among the injected bodies, such as the assemblage of olivine dolerite, quartz dolerite, teschenite, nephelite basanite, and monchiquite sills in Fifeshire, Scotland.[2]

Association with Granite and Other Quartz-bearing Species

It seems hardly necessary to go into similar detail concerning the syngenesis of feldspathoidal types and granites, granodiorites, quartz diorites, etc. Even when saturated with the ordinary siliceous materials of their country rocks, the granitic and granite-like liquids are capable of reacting with carbonates and hydrous sediments. Still more clearly would the reaction take place if the salic liquids were somewhat superheated. We have already noted the rule that nephelite syenites are genetically associated with granite in total volume greater than that visible in the basalt-foyaite association.

So, for example, the feldspathoidal rocks of the Yenisei district "alternate in age with those derived from granito-dioritic magma."[3] The syenite, nephelite syenite, and malignite of the Okanagan mountains of Washington and British Columbia are syngenetic with granodiorite, monzonite, and quartz diorite (see Fig. 53, page 135). Other illustrations are described by Weidman in central Wisconsin and

[1] A. Holmes, Miner. Mag., vol. 18, 1916, p. 71. Compare A. Holmes on the Tertiary volcanic rocks of Mozambique (Quart. Jour. Geol. Soc. London, vol. 72, 1917, p. 222).

[2] F. Walker and J. Irving, Trans. Roy. Soc. Edinburgh, vol. 56, part 1, No. 1, 1928.

[3] A. Meister, Sur les roches et les gisements d'or dans la partie sud du district d'Jenissei, St. Petersburg, 1910, p. 593.

by Penck and others at Predazzo.[1] But nowhere else is the association more strikingly evident than in the Haliburton-Hastings region of Ontario (Fig. 181). Figure 182 exhibits an analogy, where monzonite is syngenetic with feldspathoidal rocks.

The existence of such cases does not mean that quartzose rocks may not be the products of reaction between alkali-rich liquid and

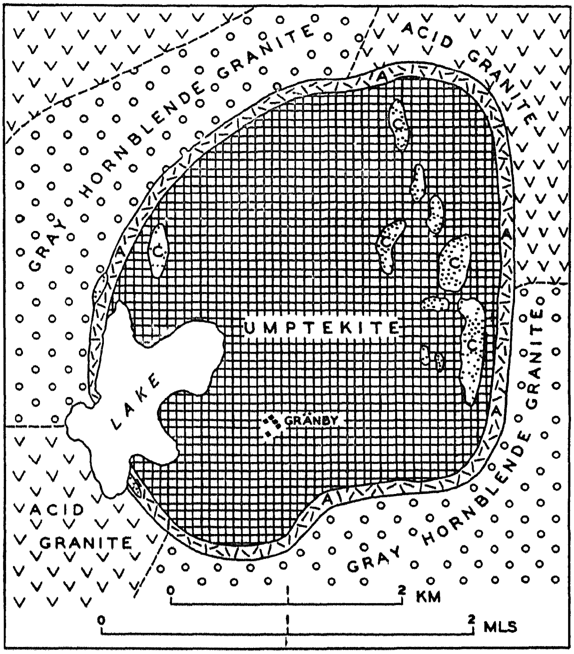

FIG. 183.—Map of the Almunge stock of umptekite with marginal aplitic phase (*A*) and inclusions of canadite (*C*). The stock cuts older granite. (*After P. D. Quensel, Bull. Geol. Inst. Upsala, vol.* 12, 1914, *p.* 129.)

acid country rock. According to Quensel, the aplitic contact phase of the Almunge stock is to be largely explained as a syntectic between umptekite magma and the intruded granite, the umptekite itself following an older intrusion of the strongly feldspathoidal canadite (Fig. 183).[2]

ERUPTIVE SEQUENCE

For a major "alkaline province," as for a subalkaline, the general theory implies a normal post-Archean order of eruption—from mafic

[1] S. Weidman, Bull. 16, Geol. and Nat. Hist. Survey Wisconsin, 1907, p. 353. W. Penck, Neues Jahrb. f. Mineralogie, etc., B.B. 32, 1911, p. 341; J. Romberg, Sitzungsber. Akad. Wiss. Berlin, 1902, pp. 673, 731, and 1903, p. 43.

[2] P. Quensel, Bull. Geol. Inst. Upsala, vol. 12, 1914, p. 161.

to felsic. Such is the fact demonstrated in many of the best studied fields. On the other hand, the sequence should be poorly or not at all manifest where Pre-Cambrian palingenetic granite reacted with carbonate rocks, locally generating feldspathoidal species. Reversal of the normal order and alternation of mafic and felsic, as well as alternation of subalkaline and feldspathoidal eruptions, are theoretically demanded at volcanic vents of the central type. That the facts actually correspond is shown in the Mont Dore, Le Velay, Le Mézenc, Cantal, and Limagne of central France; the Rhine province; Bohemia; Lipari Islands; Ascension Island; the Australian centers; and elsewhere.

Leucitic Types

So far this chapter has been occupied chiefly with the problem of the soda-rich feldspathoidal rocks and their syngenetic associates. The explanation offered for these may apply also to leucite-bearing species in Italy, the Duppau Hills, the Eifel, the Leucite Hills of Wyoming, and some other localities, but the reason why leucite was there developed or why potash should be enriched so greatly in some leucitic types remains obscure. A more or less obvious guess, following the general hypothesis, is that syntexis with dolomite or magnesian limestone might, under certain circumstances, produce the rare leucitic eruptives, syntexis with purer calcium carbonate giving soda-rich types. But neither field relations nor facts derived from physical chemistry furnish solid ground for retaining that idea. Its inadequacy is all the more to be suspected since Holmes and Harwood published their paper on the leucitic volcanic rocks near Ruwenzori, Uganda. This is another region where limestone and dolomite appear to be entirely absent among the country rocks of the eruptives. The latter include biotite pyroxenites, melilite basalts, leucitites, and potash-ankaratrites.

Holmes and Harwood conclude that

> . . . kimberlite magma—or its parent or derivatives—is likely to be the most probable source of the kind of material required . . . for the generation of leucitic rocks. The simplest means of generating the felspathic families of the latter would thus seem to involve the mingling of, or reaction between, a kimberlite or related magma with material of basaltic composition (magma or rock), accompanied or followed by appropriate processes of crystallization differentiation. . . .
>
> The hypothesis here proposed is that the magmas of mica-peridotites and olivine-leucitites are formed essentially by the abstraction of eclogite and olivine from a primary peridotitic magma under high-pressure conditions (due to great depth or high concentration of volatile constituents), and that the magmas of melilite-basalt and alnöite are formed from the same primary

magma, under conditions of somewhat lower pressure, by the abstraction of olivine and enstatite (or clino-enstatite). . . .

The hypothesis suggests that on the eastern and southeastern flanks of Ruwenzori the deep-seated parent magma first passed through the mica-peridotite stage, ascended rapidly towards the surface and consolidated after further loss of olivine, etc., as a series of intrusions of the biotite-pyroxenite suite. Meanwhile, the primary peridotite that followed up the early differentiated magma lost enstatite at intermediate depths and reached the melilite-basalt stage, afterwards ascending to be explosively erupted far and wide over the district. Subsequently, the magma behind this second main differentiate reached the mica-peridotite stage, and ascended to a level where it could consolidate as olivine-leucitite or differentiate into potash-ankaratrite and leucitite, drilling out at intervals the explosion vents in and around which these rocks are found. It seems reasonable, therefore, to regard the explosion vents on each side of the Kazinga Channel from Kichwamba to Kikorongo as the tops of what may be kimberlite pipes in depth.[1]

The suggestion regarding genetic connections among the Uganda volcanic suite, kimberlite magma, and primary peridotite magma is of great interest and in line with a conceived origin of kimberlite as described in the next chapter. In any case it seems clear that the mechanism developing leucitic and nephelitic rocks is not to be described by a single formula.[2]

General Conclusion

This chapter has discussed the feldspathoidal rocks. Some are relatively rich in alkalies, others poor. Together they make about one-half of the species generally grouped under the vague symbolical names "alkaline suite" and "alkaline class." Not all species of even that fraction are explained by the hypothesis of carbonate syntexis, an idea believed worthy of continued emphasis but not to be applied to many alkali-rich rocks or to all feldspathoidal types. Syntexis of comparatively basic, water-charged sediments, tuffs, etc., containing no carbonate whatever, has been stressed as a second genetic condition; and still other conditions, such as concentration of juvenile carbon dioxide and perhaps on rare occasions the local rise of peridotitic liquid, are also to be considered in the complex problem of origins.

The preferred theory of the alkaline group is seen to be eclectic. In it is something of every other published theory that demands

[1] A. Holmes and H. F. Harwood, Quart. Jour. Geol. Soc. London, vol. 88, 1932, pp. 428, 431, 434. See also A. Holmes, Geol. Mag., vol. 69, 1932, p. 553, where the general idea is extended to soda-rich rocks.

[2] While this book was being printed, W. F. P. McLintock (Miner. Mag., vol. 23, 1932, p. 207) published an account of the generation of leucite and aegirite with melilite, wollastonite, and diopside in a Persian marl, heated by the combustion of hydrocarbons underground. This discovery is significant.

derivation from subalkaline magmas. However, the accent is here placed in a special way. While progressive crystallization and the positive activity of juvenile gases are essential processes, they alone do not seem sufficient to account for the feldspathoidal clans. Resurgency of material from country rocks is held to be an additional control when the whole multitude of rock varieties is in question. The theory has been restated, not to proclaim a definitive solution of the comprehensive problem but to call for further examination. What are needed are experiments with the solutions engaged in igneous action and new study of the conditions in depth where the alkaline rocks have been generated.

CHAPTER XXII

ULTRAMAFIC ROCKS. MAGMATIC ORES. CARBONATITES

This chapter will outline some facts and suggestions concerning the peridotite and pyroxenite clans kimberlite, hornblendite, the primary magmatic ores, and the so-called "carbonatites."

PERIDOTITE CLAN

The peridotitic species include the following:

Species	Essential Components
Dunite..............	Olivine
Harzburgite (saxonite)	Olivine + rhombic pyroxene
Wehrlite...........	Olivine + diallage
Lherzolite............	Olivine + diallage + rhombic pyroxene
Amphibole peridotite...	Olivine + amphibole
Cortlandtite.............	Olivine + amphibole + pyroxene
Mica peridotite.........	Olivine + biotite

Vogt compiled the chemical analyses of the rock types as well as of the corresponding olivines and instructively discussed certain points in the physicochemical relations. From his tables the average compositions of cortlandtite, saxonite, lherzolite, dunite, and mica peridotite (Table 1, columns 74 to 80) were computed. Vogt accepted Schetelig's conclusion that ultrabasic lenticular masses of Snarum, Norway, crystallized from a peridotite-magnesite magma containing 5 to 10 per cent CO_2, 32 to 36 per cent SiO_2, and 51 to 52 per cent MgO.[1]

Modes of Occurrence.—Another valuable guide to the essential facts known about the ultrabasic rocks in general is Benson's world survey of their distribution, structural relations, and dates of eruption.[2]

1. With the exception of kimberlite (commonly regarded as an altered peridotite), these rocks, like anorthosites and pyroxenites, are not represented among the extrusive types, though found as nodules and angular fragments in many basaltic and allied flows, tuffs, and agglomerates. An unusual case has been described by Lausen. In basaltic tuff and cinders near Globe, Arizona, he found many olivine bombs and in addition reports the base of an olivine-basalt flow of the locality to be crowded with inclusions of olivine rock, there segregated

[1] J. H. L. Vogt, Videns.-Skrifter, Christiania (Oslo), Kl. I, 1924, No. 15, p. 14.
[2] W. N. Benson, Mem. Nat. Acad. Sciences vol. 19, Mem. 1, Washington, 1926.

by gravity. These inclusions have smooth surfaces, indicating some resorption by the basaltic liquid.[1]

2. The prevailing form of the larger peridotitic intrusions is elongated and lenticular, the masses tending to be concordant with the country rocks. Some are definitely sills, typified by one, 50 meters thick, at Kaersut, Greenland (Fig. 184).[2] Others have the general shape of laccolith or lopolith, though they may lack clear evidence of the corresponding mode of injection. Great sheets and lenses lie in the strikes of mountain chains, and many of the masses appear to have been intruded in phacolithic fashion or else as sole injections.

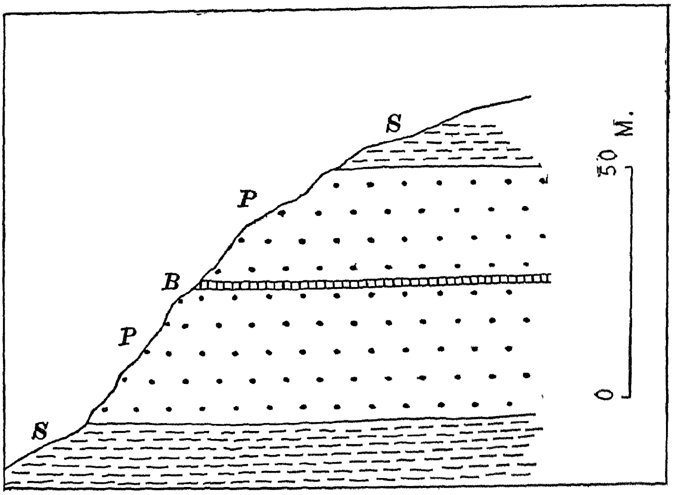

FIG. 184.—Section of a composite sill in Greenland, illustrating a close association between basalt and peridotite. *S*, Cretaceous sandstone; *P*, peridotite sill; *B*, basalt sill. (*After A. Heim, Medd. om Grönland, vol.* 47, 1911, *p.* 203.)

Usually this "green rock" facies is a composite of gabbro, diabase, or analogous types along with the peridotite.

Of specially great volume are the twenty-two bodies of ultrabasic rocks ("serpentine") in New Caledonia, with a total outcrop of 5500 square kilometers. They are strung along the main axis of the island. The largest exposed mass measures 40 by 150 kilometers. How far this "serpentine" represents true peridotite is unknown. Similarly elongated are the peridotite-serpentine bodies of the Dun Mountain district of New Zealand, where the largest mass is about 25 kilometers long and 5 kilometers in maximum width of exposure.

No peridotite body has been shown to have a bulk comparable with the more voluminous granites, gabbros, or norites.

[1] C. Lausen, Amer. Jour. Science, vol. 14, 1927, p. 293.

[2] A. Heim, Medd. om Grönland, vol. 47, 1911, p. 203; F. K. Drescher and H. K. E. Krueger, Neues Jahrb. f. Mineralogie, etc., B.B. 57 (A), 1927, p. 569.

3. Some of the sheetlike peridotites of the mountain chains may be products of the dike mechanism. The widespread mica peridotites, especially injected during the Mesozoic era, occur characteristically as dikes. Apophysal dikes from the laccolithic center of the Island of Skye have been subjected to detailed study by Harker and by Bowen. The dikes average 5 or 6 meters in width, and Bowen concludes: "The tendencies displayed by these dikes strongly suggest that peridotite freely forms only wide dikes, the more so as the proportion of olivine in it increases. In this we may see some indication of the condition of the material as intruded."[1] Camsell records many peridotite dikes, "generally only a few inches wide," intrusive into the main peridotite of the Tulameen district, British Columbia.[2]

4. Many peridotites are local, layered differentiates within gabbroic or noritic laccoliths or lopoliths, such as those distributed through hundreds of kilometers along the Ural Mountain chain, or those of Minnesota and the Bushveld Complex. Commonly these olivine-rich layers are adjoined by yet thicker layers of pyroxenite.[3]

5. Still other masses are crosscutting and stocklike in appearance; these also may be accompanied by large bodies of pyroxenite. Thus in the Tulameen district, pyroxenite, covering in outcrop 30 square kilometers, completely incloses the two major bodies of peridotite, the larger of which covers 7 square kilometers. Analogy with the Ural cases suggests for the Tulameen masses chonolithic emplacement after differentiation at some depth. Significant for their content of platinum are the Bushveld pipelike segregations of hortonolite dunite in normal dunite and coarse diallage rock.[4]

Problem of Origin.—The closeness of association between basaltic magma and many peridotites is a fact too well-known to demand elaborate illustration. The olivine nodules of basaltic and trachydoleritic volcanoes represent a manifest example. The basalt of the small Dundas neck, New South Wales, carries fragments of lherzolite,

[1] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 148, with reference to Harker.

[2] C. Camsell, Mem. 26, Geol. Survey Canada, 1913, p. 52.

[3] Leading references for the Ural bodies are L. Duparc, Arch. Sci. phys. et nat., Geneva, vol. 31, 1911; N. Wyssotzky, Mém. Comité géol. Russie, Nouv. sér., Livr. 62, 1913; A. Zavaritsky, Matér. géol. gen. et appliqué, Comité géol. Leningrad, Livr. 108, 1928.

[4] P. A. Wagner, Trans. Geol. Soc. South Africa, vol. 28, 1925, pp. 1 and 83 and Pl. XIII. Wagner concluded that the hortonolite dunite is of "pegmatitic origin" (Econ. Geol., vol. 21, 1926, p. 127). See his excellent book "The Platinum Deposits and Mines of South Africa," Edinburgh, 1929, pp. 52, 65, 72. On p. 53 Wagner noted that "big sheets of hortonolite-dunite, associated with pegmatitic diallagite, and conforming to the pseudostratification [of the Bushveld Complex] are also known."

harzburgite, and dunite, along with others of anorthosite, norite, and dolerite.[1] Harzburgite is a "feldspar-free olivine norite" and in the Harzburg district itself is intimate with norite. Wehrlite of many occurrences, a "feldspar-free olivine gabbro," is clearly a differentiate of gabbro magma.

A more indirect association with basaltic liquid is suggested, in accordance with the general theory, by the appearance of peridotites

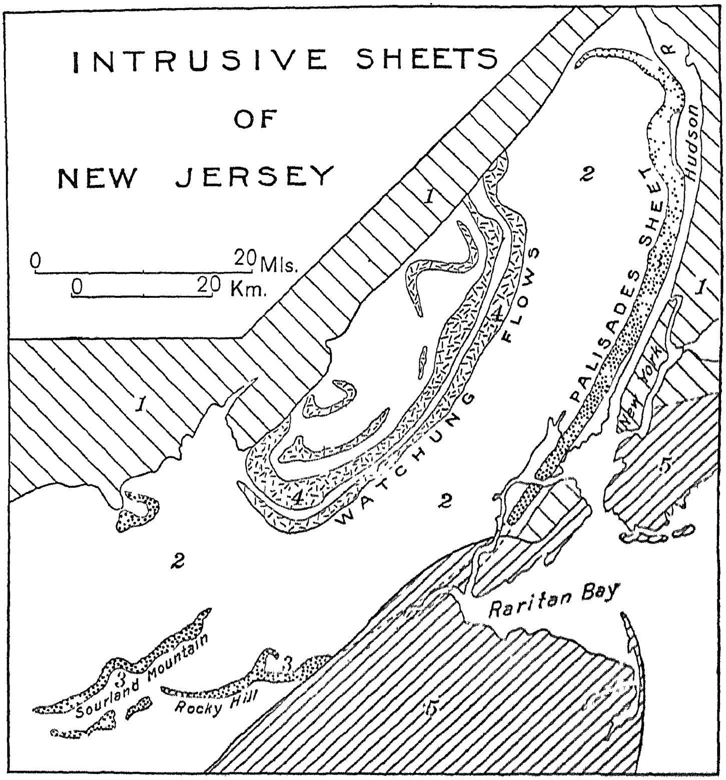

FIG. 185.—Map of the Palisades sheet, New Jersey. *1*, crystalline rocks; *2*, Triassic sediments; *3*, intrusive diabase (Triassic); *4*, extrusive basalt (Triassic); *5*, Cretaceous and later sediments.

with the "alkaline" suite: for example, wehrlite with the Monzoni rocks, the Hawaiian trachydolerite, and the monchiquite of Golden Hill, Monmouthshire. The analogous, strongly mafic picrites, limburgites, and oceanites are found in the same volcanic complexes with trachyandesite, trachyte, or phonolite, as in the Canary Islands, Réunion, Hawaii, Tahiti, and Samoa.

[1] W. N. Benson, Proc. Roy. Soc. New South Wales, vol. 45, 1910, p. 499.

Petrologists are becoming agreed about the mode of differentiation of many peridotites. In earlier chapters as well as in Table 40, we noted examples of the gravitative separation of olivine, to form strongly mafic phases of floored injections. Among them are the Palisades sheet (Fig. 185); the Insizwa, Tabankulu, Ingeli, and Tonti sheet or sheets of South Africa; the Duluth lopolith; the Inchcolm, Barnton, Ardrossan, Lethan Hill, Benbeoch, Castle Craigs, and other Scottish sills; probably also the Glen Orchy mass of Scotland and the picrite-bearing teschenitic sills of Teschen, Austria.

In similar relation to roof and floor are true peridotites, other phases of some of the injected bodies listed above; also peridotites found in the Sinni Valley laccolith of Italy (Fig. 186), in seven of the Ural "laccoliths," in the banded phase of the main Bushveld norite, and

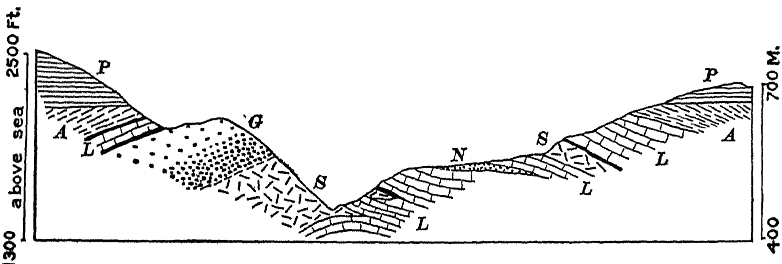

FIG. 186.—Section of the Sinni Valley, Italy. *L*, Eocene limestone, *A*, Eocene argillite; *S*, serpentinized peridotite; *G*, gabbro passing upward into plagioclasite; *N*, norite; *solid black*, granite and aplite; *P*, Pliocene conglomerate, etc. Horizontal scale, 1:30,000. (*After C. Viola, Boll. r. Com. geol. d'Italia, vol.* 23, 1892, *p.* 105.)

in the banded Raana norite of Norway. When the true nature of the Great Dike of Rhodesia (Fig. 20) becomes understood, it may possibly appear that there too gravity controlled the development of peridotite among its various ultrabasic layers.

Assuming differential density and gravity to be dominant, we still have to inquire about the units of differentiation.

Although a few petrologists like Read may here entertain the hypothesis of unmixing of basic material in the liquid state, and the units as possibly non-consolute liquids, the physicochemical reasoning of Vogt and Bowen in favor of crystal fractionation is more generally accepted (see page 327). Similarly Fermor's discovery that olivine crystals settled down in even the quickly chilled basaltic flows of the Deccan led him to suggest the development of peridotite by such accumulation.[1]

[1] H. H. Read, Geol. Mag., vol. 6, 1919, p. 368. J. H. L. Vogt, Videns.-Skrifter, Oslo, Kl. I, 1924, No. 15, p. 6. N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 145. L. L. Fermor, Rec. Geol. Survey India, vol. 58, part 2, 1925, pp. 176, 207.

On account of the high temperatures of melting and mutual solution of olivine and other magnesia-rich crystals, Bowen assumes that there is little re-solution in deeper magmatic layers; he regards the peridotites, like the anorthosites, as "rafts" of solid crystals, containing no more interstitial liquid than that sufficient to permit of their injection as comparatively wide dikes, sheets, etc.

On the contrary, Schweig postulated re-solution in depth, with the generation of peridotitic liquids. This view is shared by Beger, Berg, Niggli, Scheumann, Thomas and Bailey, and Vogt. In the case of the ultrabasic rocks of the Bushveld Complex, Wagner pointed out certain objections to the raft theory, difficulties that would be avoided by assuming re-solution of sunken crystals, and yet considered it best to leave the question open. He explained the differentiation of the layered phases of the norite by special abundance of sulphur, "a powerful mineralizer." Benson accepts Bowen's raft theory but speaks of "peridotitic magma injected as such" in New Caledonia and elsewhere. Drescher and Krueger describe the Kaersut sill as an injection of "peridotite magma." Shand believes peridotitic dikes to be products of "primary peridotitic magma." Camsell regards the peridotite and pyroxenite of the Tulameen district as having been in the molten state when injected.[1]

Whether or not re-solution of sunken crystals takes place in depth, the underlying principle of gravitative differentiation accounts for (*a*) the comparative rarity of peridotitic intrusions at visible horizons, since easy eruption of the deep-seated phase to such higher levels is not to be expected; (*b*) the small volumes of the peridotitic bodies; and (*c*) the lack of effusive peridotite in the earth's crust. To be correlated with the last-mentioned fact is the general absence of vesicular texture in the picrites, the gases of a differentiated mass tending to rise away from the ultramafic phase.

Nevertheless, the whole story of this gravitative differentiation cannot be told until we obtain some explanation of the comparative rarity of peridotitic phases in diabasic, gabbroic, and noritic sheets and laccoliths. The question involved has already been touched upon in Chapter XIV, where it was suggested, with due reserve, that such

[1] M. Schweig, Neues Jahrb. f. Mineralogie, etc., B.B. 17, 1903, p. 516. P. J. Beger, in Niggli, Gesteins- und Mineralprovinzen, Berlin, 1923, Bd. 1, pp. 474, 561. P. Niggli, *ibid.*, p. 29. F. Behrend and G. Berg, Chemische Geologie, Stuttgart, 1927, p. 75. K. H. Scheumann, Centralb. f. Mineralogie, etc., 1922, p. 519. H. H. Thomas and E. B. Bailey, Mull memoir, Geol. Survey Scotland, 1924, pp. 33, 279. J. H. L. Vogt, *op. cit.*, p. 95. P. A. Wagner, Platinum Deposits and Mines of South Africa, Edinburgh, 1929, pp. 45, 47. S. J. Shand, Eruptive Rocks, London, 1927, p. 225. C. Camsell, Mem. 26, Geol. Survey Canada, 1913, pp. 52, 67.

differentiations may have depended upon (1) some contamination of the parent magmas, particularly with resurgent gases (page 324), or (2) high-level reaction of basic liquid with country rock, causing a rapid and specially abundant generation of early-formed crystals which then sank to the deeper levels (page 354).

In conclusion, it appears probable that crystal fractionation of basaltic magma has been responsible for many peridotitic bodies. Simple gravity seems to have been a sufficient cause of accumulation of the heavy silicates. If separation by squeezing-out is another cause, its action might naturally be suspected where the crystallizing magmas of the "green rocks" were sheared along or near the soles of major thrusts. Other conditions to be considered are the precipitating effect of foreign material assimilated by basaltic liquid and the possible role of thermal or other types of convection.

However, fractionation of basaltic magma is not to be readily held responsible for the specially voluminous bodies of peridotite, such as those of New Caledonia and New Zealand. Chapter IX contains the query whether such major ultrabasic invasions of the crust were caused by convective overturn of a peridotitic earth shell, whereby primary peridotitic material became temporarily capable of eruption. This question will be further discussed in the next section, dealing with the kimberlites. Some writers hold that the peridotitic shell has a composition given by the average analysis of achondritic meteorites; this is not far from equivalent to the average analysis of wehrlite (see columns 5 and 6 of Table 63).

Kimberlite

Although kimberlite is generally grouped with the peridotites, it deserves special treatment; few rock types are more puzzling from the point of view of genesis. A number of writers have emphasized the degree of chemical correspondence with melilite basalt and also with alnöite, but so far no one has succeeded in showing definitely how either species is genetically connected with kimberlite. That this rock itself defies clean-cut description is illustrated by its strong variation in chemical composition (see column 1 of Table 63, which also bears average analyses of ordinary kimberlite and what Wagner called "basaltic kimberlite").[1]

The rock occurs almost wholly in volcanic pipes, most of which are confined to southern Africa, with a few approximate equivalents

[1] Kimberlite analyses from P. A. Wagner, The Diamond Fields of Southern Africa, Johannesburg, 1914.

in the two Americas.[1] Each pipe is narrow and some of the pipes assume with increasing depth the form of an ordinary dike of no great width. The total volume of known kimberlite is doubtless less than that of a granite stock of moderate size. An outstanding feature is the evidence of tremendous explosions when the pipes were filled with

TABLE 63

	1	2	3	4	5	6
	Range of oxide proportions in kimberlite	Average of 6 ordinary kimberlites	Average of 4 "basaltic kimberlites"	Average of 4 analyses of mica peridotites	Average of 20 achondritic meteorites	Average of 5 analyses of wehrlites
SiO_2	29.56–46.83	37 77	32.01	33.94	48 93	46.51
TiO_2	0– 2 34	1 54	1.32	4 95	....	.66
Al_2O_3	.69– 6 16	3 00	2.20	10.28	6.15	5.93
Fe_2O_3	4 18–27 40	6 75	4 82	4.59	....	3.54
FeO	2.21– 4 84	2.73	3.81	11.12	15.86	9.84
MnO	0– 01	......	.01	.16	.23	.27
MgO	10.80–39.70	30.53	35 08	20.45	18.17	23.61
CaO	2 42–10 40	3.00	7.19	5.35	7.12	7.72
Na_2O	.11– 2.55	.32	.26	.48	.67	1.17
K_2O	26– 4 32	1 28	.67	4.90	.27	.59
H_2O+	4 82–10.19	8 83	6.43			
H_2O-	.25– 7.95	2 07	.69			
(Total water)	5 25–13.30	10.90	7.12	2.96		
P_2O_5	.41– 2.15	.88	.97	.82	....	.16
CO_2	.20– 7.65	1.30	4.54			
Total	....	100.00	100.00	100.00	100.00*	100.00†

* Includes 2.60 of Cr_2O_3 and elements; this average computed by H. S. Washington (Amer. Jour. Science, vol 9, 1925, p. 362).

† Calculated as water free and to total of 100.00.

kimberlite and its many "xenoliths," the list of which includes peridotites, pyroxenites, eclogites, trap rocks, gneisses, dolomite, and even rocks comparatively rich in alkalies. Generally the kimberlite itself is pyroclastic, and no pipe filled with unbroken material appears to have been found. The known bodies are confined to regions that have escaped strong horizontal compression since Pre-Cambrian time. Those that can be dated with some approach to certainty originated not earlier than the close of the Paleozoic era.

[1] E. O. Teale (Short Paper 10, Geol. Survey Tanganyika, 1932, p. 3) states that in the Kisiriri region of Tanganyika kimberlite forms "a series of sheet or sill-like intrusions." This apparently unique case should be described in detail!

At all localities the dominant mineral constituent is serpentine. Benson's thorough review of the literature showed that by 1918 petrological opinion was becoming more agreed that the water of the serpentine in such rocks as kimberlite was magmatic, not meteoric. Later discussions of the problem tend to strengthen this view, which is supported by Benson's own observations in many regions. Thus Loewinson-Lessing argues for the late-magmatic origin of antigorite and of serpentine in general.[1]

A visit to South African pipes in 1922 led the present writer to question the widely held hypothesis that all, or even the greater part of, the serpentine is there a replacement of olivine. The high explosiveness of the magma meant a large percentage of volatiles, and water was manifestly indicated. Could one go further and suppose that much of the serpentine is a direct unchanged crystallization from the original magma, the rest of the serpentine being a late-magmatic replacement of olivine, which (for example, by local loss of water) had, also early, formed crystals, direct from the magma? This heretical conception of serpentine has been independently reached by Gisolf, whose remarkable paper on certain New Guinea rocks has not had the attention it deserves. These rocks are composed of fresh olivine and abundant antigoritic serpentine, with magnetite.

Gisolf explains the rock type by assuming

> . . . that the magma, from which this rock originated, crystallized under such a pressure that the gaseous components (notably water-vapour) could not escape and consequently were taken up into the rock substance from the very beginning of the crystallization, thus occasioning a primary origin of serpentine.

He continues:

> It may be suspected that in other peridotites, in which olivine crystallized first, the said pressure was less, so that, indeed, the gases could escape at the beginning of the crystallization, but were taken up again afterwards at the final crystallization, so that in similar cases serpentinization of olivine might be considered as an apomagmatic (hydrothermal) process.

His summary statement follows:

> If the pressure is high enough serpentine crystallizes first from a magma, which is composed of xMg_2SiO_4, $yMgSiO_3$, zH_2O; at a lower pressure the crystallization begins with olivine.
>
> When olivine and (or) pyroxene are segregated, the volatile components congregate in the upper zone of the batholite, which may give rise to high

[1] W. N. Benson, Amer. Jour. Science, vol. 46, 1918, pp. 703, 709, 718, 727. F. Loewinson-Lessing, Bull. soc. minéralogie France, vol. 45, 1922, p. 34. *Cf.* A. K. Snelgrove, Bull. Canadian Inst. Min. and Metall., April, 1931, sep. p. 28.

tension, in case they have no opportunity to escape; thus the field of stability of the olivine and (or) pyroxene is abandoned, and that of serpentine is attained, after which serpentinization of olivine and pyroxene commences.[1]

Gisolf's hypothesis seems to match the main facts known about eruptive serpentines and, as already stated, resembles that to which the author was led in 1922 when studying the kimberlite of South Africa. Experiments should test the idea that at high pressure serpentine may crystallize as directly as biotite has crystallized.

The reason for the concentration of water and carbon dioxide in the pipe channels is obscure. If the ultrabasic magma was the product of the crystal fractionation of basalt, we should not, by the orthodox theory, expect water to be abundant. Can the idea of Wagner and Holmes, that kimberlite represents indirectly (after differentiation) a tapping of a "universal" earth shell of peridotite, furnish the basis for a reasonable hypothesis?[2] Let us assume a convective overturn of this shell and relative abundance of volatiles in the upper part of the shell in its new state, the percentage of water being a function of the original pressure at the greater depth as well as of diffusion after the overturn. Since the densities of molten peridotite and plateau basalt are not far from equal, it is conceivable that the hot, gas-rich, ultrabasic melt has risen through or temporarily replaced the vitreous basaltic shell and thus come within eruptional distance from the earth's surface. Dare we look here for explanation of the gas-rich and explosive character of kimberlite? If it could be proved that the vitreous-basalt layer is comparatively thin, the idea would be more appealing. Once the pipe channels were opened, the volatiles would there be concentrated still further. They would facilitate the required differentiation of the original peridotitic magma and would tend to carry alkalies upward, from the wall rocks into the pipes, where, in fact, we observe the "alkaline" associates of kimberlite.

[1] W. F. Gisolf, Proc. Kon. Akad. Weten. Amsterdam, vol. 26, 1923, pp. 195, 197. The "regeneration" of olivine in serpentine of the Chester district, Massachusetts, has been described by C. Palache (Amer. Jour. Science, vol. 24, 1907, p. 491). An analogy is the occurrence of hortonolite in narrow veins cutting the cumberlandite at Cumberland Hill, Rhode Island (C. H. Warren, Bull. Geol. Soc. America, vol. 25, 1914, p. 451). In both of these cases it seems necessary to postulate gaseous, pneumatolytic emplacement of the olivine, with ultimate escape of fluxing gas.

W. W. Wilkman (Geotek. Medd., No. 36, Geol. Komm. Finlande, 1923, p. 65) shows how the olivine-water-serpentine reaction is reversible, its direction changing with temperature.

[2] P. A. Wagner, South African Jour. Science, vol. 25, 1928, pp. 133, 139. A. Holmes, Quart. Jour. Geol. Soc. London, vol. 88, 1932, pp. 428 *ff*; Geol. Mag., vol. 69, 1933, p. 544.

Worth noting is the strong chemical contrast between average kimberlite and average mica peridotite, the latter occurring in isolated dikes with a sporadic distribution much like that of kimberlite in its apparent arbitrariness. Both types differ essentially from the average achondritic meteorite (columns 2 to 5, Table 63). In any case a peridotitic earth shell would probably not have the same composition as any of the average peridotites that are clearly differentiates of basaltic magma.

Pyroxenite Clan

By decrease of the olivine percentage, various peridotites merge into an equally varied group of pyroxene rocks. Principal types of the igneous pyroxenites in general are bronzitite, diallagite, diopside rock, hypersthenite, and websterite. The first four species tend toward the monomineralic composition indicated by their names; websterite is essentially a highly varied mixture of monoclinic and orthorhombic pyroxenes. Averages of the analyses of bronzitite, diallagite, and websterite are given in columns 83 to 85, Table 1. Less abundant types are bahiaite (hypersthene and hornblende), koswite (mesostasis of diopside plus olivine plus magnetite), apatite-magnetite pyroxenite, and apatite-titanite pyroxenite.

The more voluminous members of this group of ultrabasic rocks resemble the peridotites with respect to both field relations and general mode of origin. Here too we appear to have gravitative separation from less basic (basaltic, pure and contaminated) magma through density differences, the units of differentiation being probably solid crystals.[1]

Floored injections illustrating this simple kind of gravitative control include the Oiseau and Maskwa River sills of Manitoba, each of which carries "augitite" at or near the base. Cooke concludes that the constituent crystals of pyroxene sank as such, while labradorite crystals rose, in the Oiseau River sill.[2] Iddings found decided enrichment of augitic material at the bottom of an intrusive sheet at Electric Peak, Yellowstone National Park.[3] The pyroxenites of the Bushveld Complex accompany chromite, peridotite, and anorthosite in the form of well-defined layers not far above the sedimentary floor of the complex. The minimum thickness of an individual homogeneous layer

[1] T. Krokström (Bull. Geol. Inst. Upsala, vol. 24, 1932, p. 202) believes he has good evidence that the pyroxene of the Breven dike dolerite and of some other basaltic types was fluid after much of the associated plagioclase crystallized, and he seems to prefer in these cases liquid unmixing rather than crystallization as the mode of differentiation.

[2] H. C. Cooke, Summ. Rep. Geol. Survey Canada, 1921, part C (1922), pp. 14, 21. Note section, p. 16.

[3] J. P. Iddings, Mon. 32, U.S. Geol. Survey, 1899, p. 82.

of pyroxenite, extending many kilometers along the strike of the igneous banding, exceeds 1000 meters. There, as in the Ural laccoliths, the pyroxenites are much more bulky than the peridotites. In Chapter XIV, page 354, we noted the possibility that reaction with the Pretoria shales was an important condition for the extraordinary showering of pyroxene crystals downward in the Bushveld magma. However, this explanation loses force when it is remembered that similar bands of pyroxenite appear in the "Great Dike" of Rhodesia (Fig. 20), which cuts granite and is not visibly associated with any argillaceous formation. The alternative hypothesis of periodic convection and resulting periodic showering of crystals is perhaps less troubled.

Other pyroxenites are intimately associated with rocks belonging to the "alkaline" series. Thus syngenesis is suggested with the Duppau theralite of Bohemia; the Monteregian essexite of Quebec; the Gran essexite of Norway; the monzonite of Monzoni and the syenites of Predazzo, Tyrol; the phonolites of the Sundance quadrangle, Wyoming-South Dakota; the phonolites of Abyssinia; the tephrite of the Cape Verde Islands; and the nephelite syenites of Ontario.

Here too the differentiation appears to have been largely controlled by gravity. The melanite pyroxenite of the Loch Borolan (Cnoc-na-Sroine) laccolith lies at or near the base of the body (Fig. 172). Shand attributes this and the more felsic, overlying phases to differentiation in place.[1]

The last chapter states the preferred hypothesis accounting for the association of diopside-rich pyroxenite with strongly alkaline rock, these being regarded as the opposite poles of the differentiation of a carbonate-syntectic magma. Yet it may well be that other conditions have ruled in some of these associations.

Like the peridotites, the pyroxenites never exhibit glassy or effusive phases. A chilled contact phase of pyroxenite in the northern Bushveld was reported by Kynaston, and similar cases have been described by Hall.[2] Nevertheless, there are grounds for doubting, with Bowen,

[1] S. J. Shand, Trans. Geol. Soc. Edinburgh, vol. 9, 1910, p. 376. J. Phemister (The Geology of Strath Oykell, etc., Memoir Geol. Survey Scotland, 1926, p. 87) believes the analogous ultrabasic phase of the Loch Ailsh laccolith to represent a distinct early intrusion, this pyroxene-hornblende rock having been fluid enough for the injection. He concludes that it does not represent an accumulation of crystals as such, derived from the overlying magma that yielded syenite and shonkinite. There are manifest difficulties with Phemister's explanation of the mass as a whole.

[2] H. Kynaston, Ann. Rep. Geol. Survey Transvaal, 1908, p. 10. A. L. Hall, The Bushveld Igneous Complex, Memoir 28, Geol. Survey South Africa, 1932, p. 296.

the existence of corresponding ultrabasic liquids. Crystal fractionation of basaltic magma, pure or contaminated, seems to have been Nature's mode of generating the voluminous pyroxenites. Some narrow pyroxenic veins may be referable to pneumatolytic action, and plainly kelyphitic shells of pyroxene around olivine are phenomena of late-magmatic reaction.[1]

Hornblendite

Rocks composed essentially of hornblende that crystallized directly from magma are rare and of small volume. Hornblende, like biotite, is abundant in igneous rocks, but the segregation of either mineral as such in magmatic chambers has been distinctly limited. The high density of hornblende would favor its concentration by gravity, were it not for viscosity or other inhibiting condition. No floored injection yet described seems to furnish hornblenditic analogues to the relatively deep-lying peridotitic and pyroxenitic layers in the Bushveld and Ural bodies. Of many basic sills the author has studied, only one shows a notable segregation of hornblende. This is the thickest of the Purcell sills at the Moyie River (page 429). Its abnormal gabbro near the floor of the sill is rich in hornblende. Even in this instance it is unlikely that the hornblende as such settled down in the sill, for this mineral appears to be a late-magmatic replacement of pyroxene. Large pyroxenitic masses have hornblendic phases, but these also may be merely products of auto-pneumatolytic change of pyroxene, already segregated or in the process of segregation.

Although hornblendite is known to be a phasal differentiate of certain gabbros, essexites, and even syenites, it is doubtful that in its existing state it has ever been separated from anhydrous basaltic magma or from anhydrous basaltic syntectics. Recent experimental studies have removed "any justification there may have been for believing that an amphibole could form from a dry melt."[2] In accordance with that conclusion is the field evidence of the pneumatolytic origin of some hornblendites.

A clean-cut illustration is found in the hornblenditic fillings of jointlike fissures in the norite of the Bushveld Complex, well seen, for example, at the Corporation quarries north of Pretoria. The metadiorite of the Mother Lode district, California, passes peripherally into very coarse-grained hornblendite, carrying accessory epidote,

[1] N. L. Bowen appears to have abandoned his earlier view (Jour. Geol., vol. 23, Supp., 1915, p. 51) that the pyroxenite of the Ural laccoliths represents "huge reaction-rims" developed in place around the dunitic bodies. As Benson points out, this hypothesis demands an incredible power of diffusion in the parent magma.

[2] N. L. Bowen and E. Posnjak, Amer. Jour. Science, vol. 22, 1931, p. 202; *cf.* E. Posnjak and N. L. Bowen, *ibid.*, p. 203.

muscovite, and quartz. Both the grain and the character of the accessory minerals point to a kind of gaseous transfer.[1] We may compare Heim's explanation of the kaersutitic segregations in the dike at Karsuarsuk, Greenland, and also Buddington's discussion of the Alaskan hornblendites. The exomorphic amphibolitization of igneous rocks and of limestone by magma is a further analogy. The author has concluded that lenticular masses of hornblenditic rock apparently crystallized from water-rich solutions moving along shear zones in dynamically metamorphosed granodiorites and gabbros of southern British Columbia. Clapp explains similarly the hornblendite interrupting the Sooke gabbro of Vancouver Island.[2] The conditions for such metasomatism are probably much like those controlling deuteric hornblendization of pyroxenite.

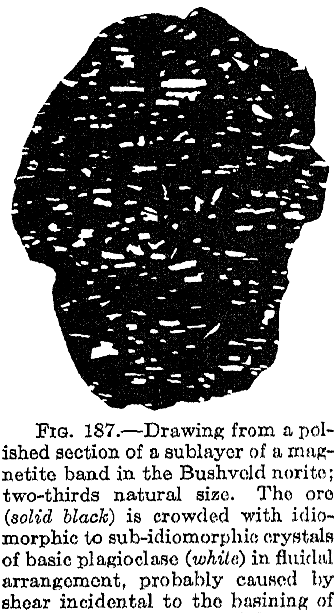

FIG. 187.—Drawing from a polished section of a sublayer of a magnetite band in the Bushveld norite; two-thirds natural size. The ore (*solid black*) is crowded with idiomorphic to sub-idiomorphic crystals of basic plagioclase (*white*) in fluidal arrangement, probably caused by shear incidental to the basining of the Bushveld Complex. What were the units of differentiation in this case? See third footnote, p. 562.

Like the anorthosites, peridotites, and pyroxenites, the hornblendites lack a chemical equivalent among the effusive rocks, nor should any be expected if these rocks have been generated in the way described. Bowen has discussed this subject, but from a quite different angle. He suggests that, if a mass of sunken or otherwise segregated hornblende crystals should be remelted or redissolved, the resulting liquid would not have the original composition of those crystals but would furnish nephelite basalt or some related rock; this hypothesis is yet to be supported by evidence that nephelite basalts are regularly associated with hornblende-bearing rocks.[3]

MAGMATIC ORES

A full treatment of the ores of magmatic origin is here out of the question, even if the author were competent to deal with this broad, complicated subject. Merely a few problems will be noted, particularly some encountered during personal studies in the field.

[1] Mother Lode District folio, U.S. Geol. Survey, 1900, p. 4.

[2] A. Heim, Medd. om Grönland, vol. 47, 1910, p. 213. A. F. Buddington, Jour. Geol., vol. 35, 1927, p. 240. R. A. Daly, Mem. 38, Geol. Survey Canada, 1912, p. 441. C. H. Clapp, Mem. 13, *ibid.*, 1912, pp. 118, 123.

[3] N. L. Bowen, The Evolution of the Igneous Rocks, Princeton, 1928, p. 273.

Magnetite Rock.—Among the differentiates of the Bushveld norite are layers of titaniferous magnetite. These occur at a comparatively high level in the body (Figs. 187, 188, 189). With maximum thicknesses reaching as much as 12 meters, the ore may be

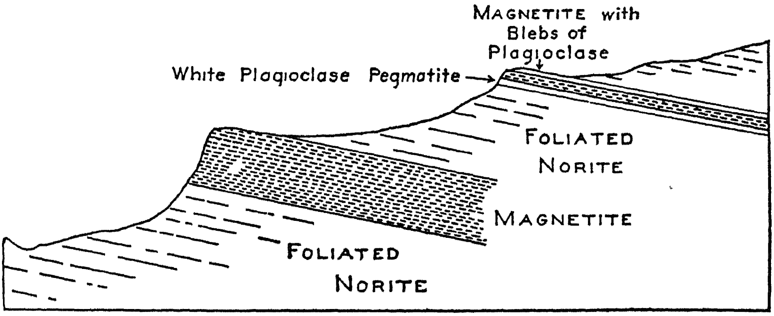

FIG. 188.—Section showing layers of magnetite in norite with primary foliation, Magnet Heights, Transvaal. (*After A. L. Hall, Ann. Rep. Geol. Survey South Africa*, 1909, *p*. 70.)

followed in outcrop for distances of many kilometers; the total length of outcrop of the magnetitic zone may ultimately be found to surpass 100 kilometers. No certain explanation of the high "stratigraphic" position of the ore has yet been given. If the upper part of the norite was erupted after the thick lower part had been emplaced and made

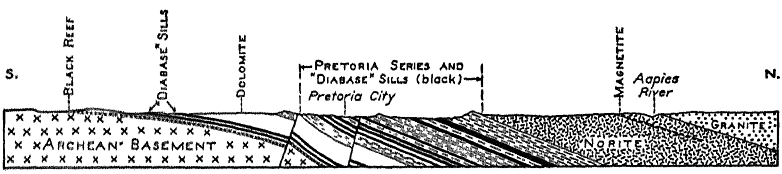

FIG. 189.—Section of the Bushveld Complex north of Pretoria, showing the high position of the magnetite layers in the norite. Scale, 1:420,000. (*From the Pretoria map sheet, old edition.*)

sufficiently rigid by cooling, one might think of the differentiation as gravitational in the upper member. Yet no compelling evidence for this hypothesis has been found, and the problem persists. The pyroxenite-peridotite-chromite-anorthosite bands already discussed are located stratigraphically far below the magnetite horizon and themselves appear not to be accompanied by important layers of magnetite.[1]

Analogous, perhaps quite homologous, bedlike masses of magnetite are reported in the gabbro of the Duluth lopolith and in the gabbro-anorthosite bodies of the Adirondacks, the Chibougamau region of Quebec, and the Bergen district of Norway.

[1] *Cf.* A. L. Hall, The Bushveld Igneous Complex, Memoir. 28, Geol. Survey South Africa, 1932, p. 276; R. A. Daly, Bull. Geol. Soc. America, vol. 39, 1928, p. 745.

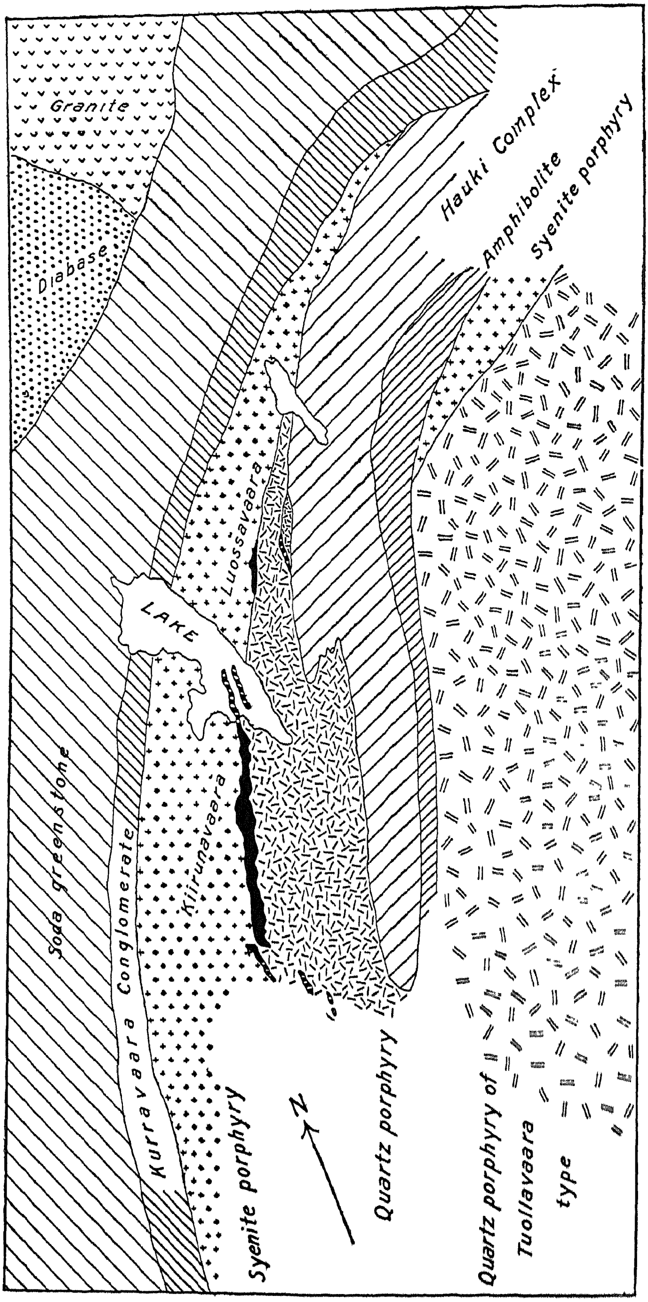

FIG. 190.—Map of the Kiruna district, Sweden. The ore bodies (*solid black*) and porphyry bodies dip steeply toward the east-southeast. Scale, 1:120,000. (*After H. Lundbohm and P. Geijer.*)

Not less intriguing, though of different association is the dramatically exposed, apatite-bearing magnetite of Kiruna, Sweden (Fig. 190). In 1898, Högbom explained its bodies as differentiates in place, from the adjacent quartz-porphyry magma. If the separation was gravitational, it must have taken place when the whole system of rocks lay flat, before they attained their present steep dips; according to Geijer, the closest student of the region, this was the original attitude of the syenite and quartz porphyries. Geijer formerly regarded the syenite as a monolithic flow of lava and the porphyries as a series of flows, though no mutual boundaries have been discovered among these above the ore horizon.[1]

Stutzer preferred to assume differentiation of liquid magnetite in depth and its injection along the contact of the syenite porphyry and quartz porphyry. Geijer now accepts this hypothesis, the ore representing a sill. He writes: "The sequence is syenite and syenite-porphyry, quartz-bearing porphyry, dike porphyry, ore, dike porphyry once more, and finally granophyre. The ore body thus reached its place during the time when a 'Nachschub' of porphyry magma was being intruded."[2] The differentiation of the ore, he thinks, was at only moderate depth below the visible rocks.

As a result of field and laboratory study, in 1914, the author suggested that, while the liquid flow of quartz porphyry, considered monolithic, lay horizontal and began to crystallize, the ore in liquid form settled down to the base of the flow. There is reason to think that the underlying syenitic body was still hot, so that the magmatic life of the quartz porphyry was greatly lengthened, thus permitting this remarkable volume of ore, differentiated in place.[3]

All three hypotheses encounter a formidable difficulty: the high melting point of a rock consisting of so great a proportion of magnetite, which in the pure state melts at 1580°. Apatite is a relatively abundant accessory but could hardly be regarded as a flux capable of giving liquidity to the ore. Geijer proposes water gas or its dissociated constituents (not halogens!) as the probable flux, a view supported by Niggli.[4] Thus having a "pegmatitic" relation to the mother magma, the ore mass would have fluidity and eruptibility.

[1] A. G. Högbom, Geol. Fören. Förh. Stockholm, vol. 20, 1898, p. 115. P. Geijer, Geology of the Kiruna District, Stockholm, 1910; Arsbok 24, No. 4, Sver. Geol. Unders., 1931, p. 6.

[2] O. Stutzer, Neues Jahrb. f. Mineralogie, etc., B.B. 24, 1907, p. 548. P. Geijer, Arsbok 24, No. 4, 1931, p. 7; *cf.* Arsbok 12, No. 5, 1918, p. 10, and 24, No. 3, 1931, p. 209.

[3] R. A. Daly, Origin of the Iron Ores at Kiruna, Sweden, Stockholm, 1915.

[4] P. Geijer, Econ. Geol., vol. 10, 1915, pp. 321-322; Arsbok 24, No. 4, 1931, p. 12; ibid., No. 3, 1931, p. 219. P. Niggli, Die Leichtflüssigen Bestandteile im

By assuming the presence of sufficient H_2O, H, and HO, we might be able to understand Geijer's important observation that, in the syenite porphyry, magnetite forms a cement between the feldspar laths of the groundmass and was the "last juice" of this iron-rich eruptive. Analogous cases have been reported: among the gabbroic projectiles in the volcanic breccias of Ascension Island;[1] in some norites and gabbros;[2] and in the magnetite basalt of Colorado.[3]

If the magnetite was the "last juice" of the Kiruna porphyry, may we not suppose that the ore settled out as the magma slowly cooled and crystallized from the surface downward? The assumed high temperature of the older syenitic body beneath should have delayed the crystallization of the lower part of the quartz porphyry.

The question remains whether future research will favor this peculiar kind of crystal fractionation under gravity, or the alternative idea of unmixing of ore and porphyry when both were in the liquid state.[4] Similar uncertainty attaches to the problem of the Bushveld Complex ore and many analogous cases.

The pyrometasomatic and pneumatolytic deposits of magnetite derived from magmas have obvious interest in connection with the preferred hypothesis for the Kiruna and related ores, but do not fall within the plan of this book.

Sulphide Rock.—Primary-magmatic ores of iron, copper, and nickel in combination with sulphur occur with the same two kinds of relation as those just described for the oxide ores. Masses of sulphide have been gravitatively assembled near the floors of basic magmatic bodies. Examples are the gabbroid Insizwa sheet (page 335); the

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Magma, Leipzig, 1920, p. 138. *Cf.* W. H. Goodchild, Mining Mag., 1918, sep., p. 71.

[1] R. A. Daly, Proc. Amer. Acad. Arts and Sciences, vol. 60, 1925, p. 66.

[2] A. L. du Toit, The Geology of South Africa, 1926, p. 148. P. A. Wagner, Mem. 21, Geol. Survey South Africa, 1924, p. 87. P. Geijer, Förh. Geol. Fören. Stockholm, vol. 52, 1930, p. 391. J. H. L. Vogt, Jour. Geol., vol. 29, 1921, pp. 629, 634. A. N. Zavaritsky, Econ. Geol., vol. 22, 1927, p. 678 (references).

[3] H. S. Washington and E. S. Larsen, Jour. Washington Acad. Sciences, vol. 3, 1913, p. 449. Other instances are given by H. Rosenbusch, by C. F. Tolman and A. F. Rogers (A Study of Magmatic Sulphide Ores, Stanford Univ. Pub., 1916, pp. 21, 67). W. Lindgren (Mineral Deposits, 3d ed., New York, 1928, pp. 121, 125) describes the iron-rich mesostasis of some basic rocks and writes of "melts" of oxides of iron. Unless the magnetite of the Bushveld Complex was liquid, it is hard to understand its content of isolated, sharply idiomorphic crystals of basic plagioclase, forming 10 to 15 weight percentage of certain sublayers of the ore (Fig. 187).

[4] *Cf.* J. F. Kemp, 19th Ann. Rep. U.S. Geol. Survey, part 3, 1899, p. 417; J. H. L Vogt, Norsk Geol. Tidsskrift, vol. 1, No. 2, 1905, p. 6; also views of Boeke, Eitel, and Berg (p. 329).

Bushveld norite (Wagner); the norite of the Cuyamaca region, California (Hudson); the Oiseau and Maskwa River sills, Manitoba (page 334); and the Petsamo region of Arctic Finland (Hausen).[1]

That the sulphidic masses separated because of immiscibility in the liquid state is now commonly believed by petrologists; the analogy with artificial mattes of the furnace is close.

The prolonged controversy about the origin of the Sudbury ores (see Figs. 146 and 147) has had excellent by-products of detailed mineralogy and petrography, including illustrations of replacement and other effects of late-magmatic action, but in spite of opposing opinions the original gravitational theory of Coleman and Barlow seems essentially sound. This theory has recently been restated, with new evidence, by Coleman, Moore, and Walker.[2]

The greatly contrasting hypothesis, emphasizing infiltration, has been summarized by Lindgren, as follows: The Sudbury ores were "in greater part formed by replacement of silicates by a very liquid melt charged with sulphides and developed by differentiation in a magma reservoir in depth [that is, below the chamber now occupied by the 'norite']"—an opinion shared by Howe and by Bateman.[3]

The metasomatic and other reactions of the sulphides with the surrounding silicates, described by Tolman and Rogers, Knight, Wandke, Phemister, and others, are just what might be expected if the Coleman-Barlow theory is true. The low melting temperature of the sulphur and its strong vapor tension at temperatures well below those where the silicates crystallized, coupled with the presence of water in the complex system, appear to represent ample conditions for late-magmatic shifts of material. Other favorable conditions were the long duration of the magmatic state in the deeper, more basic part of the thick Sudbury sheet, and also the inevitable displacement of liquid and gaseous constituents of the magma, as the rocks there slowly cooled and contracted. If the pronounced basining of the sheet continued during the prolonged solidification of the norite and still later solidification of the sulphide rock, then displacements of the ore, both upward and downward, would necessarily result.[4]

[1] P. A. Wagner, Mem. 21, Geol. Survey South Africa, 1924, p. 149. F. S. Hudson, Bull. Dept. Geol. Univ. California, vol. 13, 1922, p. 239. H. Hausen, Bull. Comm. Géol. Finlande, No. 76, 1926, p. 80.

[2] A. P. Coleman, E. S. Moore, and T. L. Walker. Univ. Toronto Studies, Geol. Ser., No. 28, 1929.

[3] W. Lindgren, Mineral Deposits, 3d ed., New York, 1928, p. 902. E. Howe, Econ. Geol., vol. 9, 1914, p. 521. A. M. Bateman, *ibid.*, vol. 12, 1917, p. 426.

[4] Compare R. D. Hoffman's account of the Vlakfontein sulphide ore, Transvaal (Econ. Geol., vol. 26, 1931, p. 202).

On the other hand, no advocate of the replacement theory has succeeded in explaining adequately the general concentration of the sulphides at and near the base of the sheet. Nor have they sufficiently regarded the perfect analogy at Insizwa Mountain, where the infiltrationists have similar trouble in supporting their thesis.[1]

In this problem the general geology and petrology, particularly the stratigraphic position of the sulphide bodies, must be considered as much more significant than the results of the most intensive study of polished sections of ore and rock. Therein Coleman showed true tact—the ability to see the forest in spite of the trees—and his main position remains unshaken, even after a long attack by able critics. Although many of the trees were transplanted, the forest remains, clearly visible to the unprejudiced eye. We may well distinguish two processes at Sudbury: differentiation of the sulphides from the norite and their subsequent migration within the norite itself and also into the country rocks at the floor.[2]

Carbonatites

That carbonates are primary crystallizations from magma is the expressed opinion of many petrologists, including, among recent writers, Barth, Brauns, Brögger, Collins, Eskola, Kranck, Ramsay, Schetelig, Schuster, Stutzer, J. H. L. Vogt, and T. Vogt.

Much more controversial is the supposition of a direct magmatic origin for carbonate-rich rock. The vapor pressure of magnesium carbonate or calcium carbonate is too high to permit us readily to credit the fusion of the pure carbonates in the earth's crust. On the other hand, the solution of these salts in silicate magmas, especially when somewhat hydrous, would not cause vapor pressures greater than those supportable by overlying rocks of moderate thickness. In fact, a large number of carbonate-bearing species of rocks have been described as direct magmatic products. Brögger's views (in part at least supported by Eitel, Schetelig, and Goldschmidt) concerning the carbonatites of the Fen region are well-known. A. and R. Brauns believe magmatic carbonatites to be represented at Laacher See. Barth finds various carbonate-rich pegmatites of Norway to have the marks of a similar origin. Barbour and Coomaraswamy were led to suspect actual fusion of limestone in China and India respectively. According to Daly, many dikes of carbonate-hydrate-serpentine dikes

[1] *Cf.* W. H. Goodchild, Inst. Mining and Metallurgy, 1916, sep. p. 11.

[2] N. L. Bowen (Jour. Geol., vol. 30, 1922, p. 558) suggested a resurgent origin for some other magmatic sulphide bodies, explaining them as due to reaction with pyritiferous shales of the intruded formations.

cutting the kimberlite of the Premier Mine, Transvaal, are probably to be classed as magmatic.[1]

Carbonatite magmas should not be assumed to have crystallized as straightforward series of minerals which were stable from the start. In such gas-rich solutions, auto-pneumatolysis and auto-metasomatic replacement of early minerals must have been more or less lively. Hence the arguments of Bowen and others against the magmatic origin are not conclusive. The case of the Fen rocks points to the necessity of defining terms, and specifically to decide when a hot gas-rich solution ceases to be called a magma. On the other hand, the carbonatites of the Premier Mine seem to show good evidence of having been truly magmatic. The author has suggested that this magma was largely composed of resurgent material, derived from the Great Dolomite in depth. But regarding this detail, as in the case of the general problem of the carbonate-rich rocks, unanimity of opinion is likely to be long delayed.

Concluding Remarks

Each of the ultramafic and ultrabasic species so sketchily treated in this chapter has its own unsolved problems. There is more mystery than clear indication of modes of evolution. Most of the types and a great number of others transitional into feldspathic species, as well as chromitite, are characteristic of zones of primary banding in igneous masses—an extraordinarily baffling phenomenon. Other questions have been raised concerning the respective parts played by reactive assimilation, magmatic gases, crystal fractionation, liquid unmixing, and the high heat of the depths. These are leading topics of the preceding chapters, the data of which should therefore be considered when estimating the tentative ideas on the subsilicic rocks, where again petrology has progressed little beyond the stage of suggestions.

[1] See the following: G. B. Barbour, Bull. Geol. Soc. China, vol. 2, 1923, p. 35; T. Barth, Norske Videns.-Akad., Kl. I, 1927, No. 8, p. 111; A. and R. Brauns, Centralbl. f. Mineralogie, etc., 1925, Abt. A, p. 97; R. Brauns, *ibid.*, 1926, Abt. A, p. 1; W. C. Brögger, Das Fengebiet, Oslo, 1921, pp. 194 *ff.*; A. K. Coomaraswamy, Quart. Jour. Geol. Soc. London, vol. 59, 1903, p. 91; R. A. Daly, Jour. Geol., vol. 33, 1925, p. 659; H. von Eckermann, Geol. Fören. Förh. Stockholm, vol. 50, 1928, p. 395; W. Eitel, Über die Synthese der Feldspatvertreter, 1925, pp. 139 *ff.*, and Die Naturwissenschaften, 1927, p. 150; O. H. Erdmannsdörffer, Centralbl. f. Mineralogie, etc., 1922, p. 363, and Grundlagen der Petrographie, Stuttgart, 1924, p. 205; J. Koenigsberger, Schweiz. Min. u. Petr. Mitt., vol. 10, 1930, p. 142; E. H. Kranck, Fennia, vol. 50, 1928, pp. 70 *ff.*; J. Schetelig, V. M. Goldschmidt, and O. Stutzer in Brögger's memoir on the Fengebiet, pp. *xi*, 246, 249; K. H. Scheumann, Centralbl. f. Mineralogie, etc., 1922, p. 521; J. H. L. Vogt, Videns.-Skrifter, Oslo, Kl. I, 1924, No. 15, p. 14; P. A. Wagner, Mem. 20, Geol. Survey South Africa, 1922, p. 43.

CHAPTER XXIII

PRINCIPLES AND PROJECTS

Here and there we have noted the lack of data vital to a stable theory of the eruptive rocks. Uncertainty of data tends to paralyze or defeat effort in a limited program of geological investigation. All the greater is the risk of wasting labor when one attempts a general theory of the earth, where leading premises are still inadequately supported by facts in hand. Yet there may be method in such madness. The recent history of physics shows the power of a general theory, even a mistaken theory, as it focuses attention on essentials. Random researches, not guided by a system of thought, have occasionally brought forth good fruit, but a multitude of others have filled the library shelves to little purpose. These the scientific and therefore scholarly investigator must examine as he tries to find wheat in the chaff. So much time and energy go to such work that for him the enormous bulk of the unrelated publication is proving a menace. Chemistry, astronomy, and biology, like physics, have distinctly bettered the situation by steady emphasis on the value of synthesis.

Physical geology faces the same grave problem, and, in spite of many lacunae in our knowledge, it seems already seasonable to try for a picture of the earth's interior, where the secret of igneous action lies. In doing this one takes a big risk—the risk of being greatly wrong. However, proving the error should enrich geological science, because the corresponding research and discussion inevitably deal with fundamentals. To use in all desirable completeness the method of multiple hypotheses, that golden principle of science, can no longer be the ambition of the individual worker. It is the job of a whole profession. On the other hand, the individual can bring whatever experience, learning, and tact that may be in him to choose reasonable basal assumptions, deduce their consequences, and compare these with the facts of Nature. Workers have done this in other fields. Each has put up his wickets. Colleagues and successors have bowled at those wickets, and the game of science has gained much from the practice. Wickets are not likely to stand indefinitely, but the game remains healthy and eminently productive. New facts and principles of great price have come to light because individuals have taken their courage in their hands.

It is indeed bold to propose the theory outlined in Chapters IX to XXII. It cannot fail to need mending at many points; yet not all of it, for the theory is eclectic and bears the solid, definitive conclusions of many masters of earth science. The crust-substratum-injection hypothesis has been elaborated to marshal these data on a single chain of thought and so to try to advertise them still more. And then there has been the second incentive—the wish to advertise the unknown, to appeal for future research where research seems to promise vital results. If the reader will believe this, he may perhaps forgive any apparent dogmatism in this book. Thus some bald statements, made in the interests of brevity and simplification, may be understood as perhaps sins of style, not as indications of a mind made up.

What little ground there is for dogmatism will, it is hoped, become still more evident from the following remarks on outstanding points. Every item of the proposed theory invites testing by special studies in field or laboratory. The questions involved are of two sorts. One group has arisen automatically with the growth of the theory. The other group, inherited from the ablest geologists, is independent of this particular theory and is worthy of the best professional efforts.

First, there is the assumption that we fairly appreciate from the start just what is the petrological problem. Notwithstanding its defects, the rock classification so largely used by the geologists of the last fifty years does give a good idea of the variety of the igneous species. There has been some arbitrary grouping in map and memoir: for example, tonalites and granodiorites with granite, hornblende gabbro with diorite, latite with andesite. There has been some arbitrary separation, as certain essexites from gabbro and certain trachydolerites from basalt. Nevertheless, thousands of maps and chemical analyses have already shown the approximate range of specific characters of the visible eruptives. The practicality of any drastic change of the rock classification to be used in mapping is a serious question. If the change be made, some method of reducing to a common standard the meaning of maps made on the two bases, new and old, will have to be provided.

In any case numerous and good chemical analyses must always be essential to any improvement of world petrography. This desired end will be reached the sooner if the particular studies of rock chemistry suggested by the theory of the present book are made. In illustration may be cited the need of further chemical studies of the plateau basalts all over the earth; of the quartz gabbros, quartz norites, and quartz diabases; of the anorthosites, oceanites, peridotites, and melilite basalts.

Chapter III has something to say about the relative and absolute volumes of single igneous bodies and about the importance of the statistic for any theory of petrogenesis. It is there pointed out that these data should be enlarged by systematic measurements in all the continents as well as on the islands. Is it too much to hope that authors of geological maps shall give, as far as possible, such quantitative information?

Good recording in the field and the advance of sound petrological theory both depend upon a sufficient nomenclature for igneous bodies, considered as geological units or constituents of the earth's crust. For our world science the system should be unequivocal, internationally acceptable, and possessing all possible objectivity, with maximum freedom from doubtful conclusions about modes of origin. Much misunderstanding will be avoided if observers and writers are faithful in the use of words with rigorous definitions. Agreement of workers to be faithful is probably easier than their agreement about definitions. For example, should Gilbert's well-characterized name "laccolith" be given to thoroughly crosscutting injections or to those not emplaced by lifting of their roofs? The good field observer has a lively consciousness of the genetic differences of laccolith, lopolith, phacolith, and harpolith. Is it not best to define "batholith" objectively rather than in terms of origin? In this book some batholiths have been speculatively explained, and it has seemed advisable to coin the word "abyssolith" for each of the bodies so visualized, but the new term can never replace "batholith" in the working vocabulary of the field geologist or easily find favor with those petrologists who do not believe in a vitreous, eruptible layer beneath the earth's crust. Is it mere pedantry to insist that large, irregular bodies, crosscutting but definitely proved to have been emplaced by pure injection (mechanical parting) of the crust, should be set apart from the more mystery-laden batholiths? If for those injected masses the name "chonolith" is unsatisfactory, should not another name be invented? Is there not some convenience in using technically the adjective "composite" to describe bodies formed by successive intrusions of different kinds of magma, and "heterogeneous" for a magma erupted in a single act but of non-uniform chemical composition?

No general theory of petrogenesis can be properly evaluated until we have learned many new facts about the physics of rocks, rock melts, and the earth as a whole. Experimental studies in this wide field are needed in many directions, including determinations of: densities of crystalline and vitreous rocks at all temperatures up to white heat; changes of density with metamorphism; coefficients of compressibility, rigidity, strength, viscosity, thermal conductivity, and thermal

expansion, all at varying temperature and pressure; latent and specific heats of rocks, including, if possible, the values at high pressures. The wise petrologist himself feels responsible for at least one modest contribution to the vital physics of rocks: he refuses to publish the chemical analysis of a rock without appending a statement of its density.

Earlier chapters have dwelt on the importance of the relation between all-sided pressure on rocks and their melting intervals of temperature. The petrologist ought to know how nearly the Clausius-Clapeyron equation holds in the case of multicomponent rocks; on this information depends sound deduction as to the amount of superheat possible in erupted magmas.

The petrologist cannot be satisfied with the existing data about thermal gradients in the rocks near the earth's surface. He needs many more careful measurements, as well as full information concerning the kinds of rocks traversed, their geological history, and the relation of borehole to rock structure. Moreover, we have seen that the results of estimating gradients in depth have hitherto been vitiated by failure to allow for systematic variations of each so-called "constant" used in the calculations. Here is a subject for difficult but essential investigation.

The framer of an earth theory is particularly disturbed by uncertainty about the amount of radioactivity in the planet. Can the physicist ultimately lay this ghost of doubt concerning one of the sources of terrestrial energy? Above all, the petrologist will applaud the physicist who discovers the cause of the atomic break-up. Would this discovery support or discountenance the geologist who concludes that there is no evidence of net accumulation of temperature in the earth's body? While awaiting the answer, the petrologist would like to know how careful has been the sampling of granite and other standard voluminous rocks studied with the electroscope.

Thoroughly desirable is more information about the efficiency of another kind of furnace: that "fired" by reactions among the gaseous and other components of erupted magmas. This question affects both the volcanologist and the student of plutonic activities.

The volcanologist will welcome also the results of additional experiments on the solubility of gases in rock matter at various temperatures and pressures. Until such facts are available, the argument for two-phase (liquid-gas) convection must be rated as speculative to a considerable degree.

Other experiments would test the importance of the crystal-liquid type of two-phase convection, and the assumption of gravitational separation of the differing parts of a heterogeneous magma. Why

are some basaltic (diabasic, gabbroid) sheets differentiated, apparently by crystal fractionation, and other sheets of similar thickness and average composition are not differentiated?

Ever more clearly is a good general theory of petrogenesis to be based on geophysics. This science is young and its results so far are to be taken with special caution. Their relative meagerness is a grave danger and here the synthesizing geologist can go wrong. Two illustrations will suffice.

The testing of isostasy and the search for the distribution of strength in the globe have been too long governed by the Pratt-Hayford hypothesis of isostatic compensation. As noted in Chapter IX, the geologist is likely to be much more sympathetic with a modified form of the Airy hypothesis, though the scheme of densities suggested in this book implies that the modification should be considerable and involves a principle not entertained by Airy. The future will decide whether the labor of computing gravity anomalies and deflection residuals on some such basis would be justified.

The value of the seismological method of locating discontinuities in the earth's body needs no emphasis. How shall the changes of wave velocity at these discontinuities be made to tell us definitely about the petrographical nature of the earth shells so separated? Are the cautions recommended in Chapter IX superfluous?

The geologist asks whether Oldham and others are right in postulating a fluid (liquid) core in the earth, for, if so, reasoning about the distribution of strength, the loci of isostatic adjustment, and deformation of the crust is bound to be affected. If the core, at pressures exceeding one million atmospheres, reacts as a liquid to seismic vibrations, it seems inevitable that the temperature of the core is extremely high—a temperature to be duly connected with the temperatures at all higher levels. Hence the petrologist on his part is interested.

Associated is the question of thermal convection in the earth's body. If possible at all, can it be other than of the "tandem" kind suggested in Chapter X?

If future research should corroborate the idea that, except for a true, relatively thin crust, the silicate shell is vitreous, can this shell at the high temperatures implied by the state of the matter be anywhere durovitreous?

When more astronomers return home from their excursions to the distant nebulae and galaxies and resume constructive work on the origin and history of our planet and its satellite, shall they not add to the facts for petrological theory? Can they tell us more clearly what should have happened when the earth liquefied? Was stratification according to intrinsic density established during the condensation

from the gaseous cloud? Can estimates be made of the internal temperatures then developed? Is the moon a daughter of the earth, so that we can learn from the moon's density something about the material that constituted the outer earth shell whence the moon came long ago? Will the astrophysicist of the future approve the speculation that the stony meteorites represent the bulk of the earth's silicate shell?

The structural geologist himself is deeply concerned with the dour problems about the earth's interior, and his own findings are to be respected also from the side of the geophysicist and cosmogonist. Will the geologists of the next generation be compelled to recognize the principle of continental migration, implying simultaneous compression and tension in the crust? What would be the essential conditions for the migration? Those speculatively suggested in Chapter XI include a substratum of practically zero strength and of density slightly less than the mean density of the crust, and a departure of the crust from the level, sufficient to compel the low-slope sliding or convective dragging of continental blocks. Is any other set of conditions competent to explain the earth's facial expression? Does the hypothesis of continental migration account for provincial igneous action, typified by that of the cordilleras on the one hand and by fissure eruption of the Atlantic region on the other? Does the crust-substratum-injection theory sufficiently account for the "ascensive force" that brings magma to and above the earth's surface? Shall not the geologists of the future prove still more clearly the essential contrast between the eruptivity of the early Pre-Cambrian and post-Cambrian eruptivity? Can they not aid the petrologist who tries to account for the dominance of granitic eruption during that earlier era, the apparent restriction of anorthosites in large masses to the late Pre-Cambrian, and the extraordinary development of quartz-bearing diabases, gabbros, norites and the like, also during the time just preceding the Cambrian?

Finally we glance once more at the main problem essayed by the petrological specialist—the causes of the variety of the igneous rocks. With present information it seems probable that all of these were ultimately derived from primitive basic magma. From that original liquid, Sial and Sima became separated, by repeated crystal fractionation, aided by gaseous transfer and perhaps by liquid unmixing. A leading question is concerned with the amount of reaction between Sial and Sima and the resulting increase of diversity among eruptive species. Has the heat required for the reactions during many petrogenetic cycles been supplied largely by a vitreous basaltic shell? Has material of a still deeper peridotitic shell occasionally risen through

the basaltic layer to react with the Sialic part of the crust? Have important masses of magma been produced or modified by syntexis, in its various forms of pure melting, selective fusion, and assimilation? What are the respective parts played by juvenile and resurgent gases in the drama of volcanism? Until these queries are answered we cannot complete the list of Nature's "units of differentiation" or adequately picture the development of the visible eruptives. Nor can this be done without further scrutiny of the power of simple gravity, the principle of the wine press, and the principle of resurgency in general.

Now and for long years to come petrologists will be occupied with these complex riddles. If the present book adds stimulus toward such researches, its purpose shall have been largely accomplished. There is a "world of work" to be done!

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